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THE OPERATION OF HFTF TO TEST THE MIT 12 T COIL

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THE OPERATION OF HFTF TO TEST THE MIT 12 T COIL

The MIT coil was tested in HFTF to a peak field of very nearly 12 T. The accomplishment is note worthy as a demonstration of "reactor relevant" superconductors to high field in a realistic coil environment. Just the operation of the High Field Test Facility (HFTF) in providing the necessary test conditions is also no trivial feat. This note reports the work involved in testing the MIT 12T coil, with emphasis given to the test facility itself. Data specific to the MIT coil are relegated to appendices.

ASSEMBLY OF THE MIT COIL IN HFTF

For inclusion in the HFTF coil set for test, the MIT coil was placed in a steel cannister especially fabricated by LLNL for that purpose. Dimensions of the cannister are detailed in Fig. 1. The material was 316 stainless steel. Its primary purpose was to support the two Nb_3Sn sub-coils of HFTF against the tremendous axial centering forces present during operation to full field. Figure 2 shows the MIT coil situated in its test position in HFTF. The outer cylindrical wall of the can was sized to support the total load with adequate safety margin.

The MIT coil is constituted of three double pancakes (denoted A,B, and C). The inter-pancake splices and the two current terminals projected radially outward from the coil, essentially on the midplane of HFTF. Space for these splices was provided between the NbTi sub-coils of HFTF by separating them with solid, 50-mm thick, steel blocks. Electrical insulation around the splices and terminals was provided by shimming with strips of NEMA G-10 of various appropriate thicknesses. The shims were also wedged in tightly enough to provide mechnical support against lateral deflection under Lorentz forces.

Vapor cooled current leads rated at 20 kA were purchased from American Magnetics, Inc. to deliver current to the MIT coil. Buswork between the bottoms of these leads and the coil terminals was constructed of 13x51 mm^2 copper bar stock, traced with MF-Nb_3Sn composite conductor (surplus from winding the HFTF Nb_3Sn sub-coils). Joints between the MIT coil and the buswork ends were soft soldered using 60Sn-40Pb solder and bolted.

Helium at supercritical pressures was delivered to the MIT coil through a heat exchanger system provided by MIT. The system consisted of a counterflow heat exchanger located in the dead space above the HFTF coil set and a final heat exchanger located in the bore of the coil (Fig. 2). Cryogenic valves to select alternate flow paths (cf. the schematic of Fig. 3) were also a part of the package provided by MIT. Control of the pressure and flow of the helium was accomplished in a system external to the 2 m cryostat consisting of a valve panel, a LN_2 temperature precooler, a VJ delivery/return line, a counter flow heat exchanger to warm the gas before flow measurement, a mass flowmeter, and temperature sensors and pressure gages at various points on the flow paths (cf. the schematic of Fig. 4).

COOLDOWN

Cooldown of the HFTF/MIT 12T ensemble was accomplished using the Airco refrigerator--at first using only the LN_2 precooler for cooling power, then later starting the turbine when return gas from the cryostat had dropped sufficiently in temperature. Figure 5 displays the cooldown record of the October run and Figs. 6 and 7 show that of the January run. Both records emphasize that the most dramatic results were achieved in the first three days of cooling before the turbine was turned on. Without the turbine, the coil temperature was lowered to ~100 K. The temperature was dropped an additional 50 K using the turbine; but great care, constant attention to the refrigerator controls, and three to four more days were required. In the January run, due to delays caused by the data acquisition computer, the coil temperature was allowed to warm back to about 100 K before transferring LHe. The amount of liquid required to complete cooldown and fill was not noticebly greater than in the October run where liquid transfer was begun with the coil temperature around 60-70 K. Several days of effort by a 3-5 man crew could have been saved by dispensing with the turbine for further cooldown and beginning immediately to transfer liquid when the coil temperature reached ~100 K.

During the January run, liquid transfer was begun initially from a 4 kl dewar borrowed from MIT. The transfer from this dewar was relatively slow compared to transfer from our own 10 kl dewar. Using the 4 kl dewar in that run, five hours elapsed before liquid was measureable in the 2 m cryostat. In another two hours, the level reached 50 % on the lower probe (see Fig. 8 for LHe volume in the 2 m cryostat vs. indicated level). All of the initial 3 kl in the 4 kl dewar had been transfered in those seven hours.

The rate of dumping liquid from the 4 kl dewar was unnecessarily slow (~400 $l \cdot h^{-1}$). The reason was discovered when we switched over to transferring from the 10 kl dewar. The section of transfer line that remains in the 2 m cryostat for either connection was pushed against the bottom of the cryostat leaving only a narrow slit for liquid to escape. When this situation was corrected the dump rate of liquid from the storage dewar was increased more than twofold to 980 $l \cdot h^{-1}$.

Some interesting insights to the cryogenic situation in HFTF can be gleaned from the cryostat fill data. For example, with the 980 $l \cdot h^{-1}$ dump rate, the accumulation rate in the 2 m cryostat was only about 600 $l \cdot h^{-1}$ even when liquid had covered the coil. The boiloff rate at high liquid level was later measured to be no greater than 180 $l \cdot h^{-1}$. This implies that losses in the transfer line from the 10 kl dewar consume at least 200 $l \cdot h^{-1}$. To put this in perspective, it should be realized that if we tried to maintain constant level in the 2 m cryostat by throttling the flow through this line, it would be necessary to use about 380 $l \cdot h^{-1}$ from the storage dewar just to maintain level in the 2 m cryostat. The transfer line losses should be reduced; if they cannot be reduced, only very rapid transfers should be considered.

The rate of liquid consumption is not the same at all levels in the 2 m cryostat. As much quantitative information as possible was extracted from strip chart records of the LHe level during these runs. The essence of these records as they relate to variation in boil off rate is displayed in Figs. 9 and 10. There are elements of chronology that influece these records (for example, time since the previous fill, the proximity in time to an event that drastically changed the boil off rate, etc.) but on the whole they are relatively consistent. It can be said at least that when the level is very low on the coil (after having been full) the rate of liquid consumption drops to ~40 $l \cdot h^{-1}$. When the cryostat is very full (in the range needed for safe operation), the boiloff rate rises to as high as 180 $l \cdot h^{-1}$. The magnitude and variation of the rate of consumption can be explained in part (but not entirely) in terms of conduction down the inner wall of the 2 m cryostat, which is nearly 5-mm thick. I suspect the foam plug as a virtual heat leak that contributes a significant heat load for any practical test period. Careful thought should be given to redesign of the portion of the cryostat above the coil, because a boiloff rate of 70-80 $l \cdot h^{-1}$, limited mainly by the vapor cooled lead losses, should be achieveable.

PRELIMINARY ELECTRICAL TESTS

In the October run, coil testing was delayed initially due to an error in electrically connecting the seven individual coils constituting HFTF and the MIT 12 T test coil so that all contributed in the same field direction. The error occurred because of a simple labeling mistake on the power supply leads to the six HFTF subcoils. The mistake was not discovered previously in tests of the HFTF coil set alone because it was, of course, not important until another coil was included. However, the discovery of the error, and the seriousness of the consequences had it not been discovered, emphasize the importance of seemingly mundane and redundant checking before operating so complex a system.

Because of this delay, the first period of testing during the October run was confined to check-out of the electrical equipment (power supplies, breakers, etc.) and the cryogenic electrical joints. MIT coil joint resistances are reported in a memo from M.O. Hoenig attached as Appendix A. Pertinent comments to the Hoenig memo are included in a letter from myself attached as Appendix B. In addition to these measurements, we determined the total resistance of the buswork (including all joints) connecting the MIT coil to the 20 kA vapor cooled leads. The resistances, constant vs. current and time at all current levels up to the 15 kA used for measurement, were 0.13 micro-ohm for the negative bus and 0.083 micro-ohm for the positive bus. At full current (20 kA) a heat load of 85 W (117 $l \cdot h^{-1}$) would result. This should not be considered <u>good</u> performance, but since the load was not large compared to other loads (180 $l \cdot h^{-1}$ standby at safe operating level) and temporary (only present at full current), it was acceptable.

COIL TESTING

Actual testing of the MIT 12 T coil at full current and field was carried out during only three days of the October and January runs (October 30 and January 28 and 29). The October test was foreshortened by leaks in the MIT cryogenic package. The January run was halted by failures of two of the three induction heating pulse coils required for stability testing in the MIT coil. In spite of these obstacles, which prevented full completion of the proposed test plan, a great deal of useful information and experience was obtained--information that will be invaluable in designing and building future coils with conductors of this type.

RESULTS

Results of the October test are included in Appendices A and B as already mentioned. The results of the January tests are being prepared for presentation at the 1985 CEC/ICMC, Cambridge, MA. The following qualitative conclusions can be drawn from the results: (1) The cable-in-conduit conductor provides a potential means of obtaining high current densities at high fields. (2) The cable-in-conduit conductor provides a means of taking advantage of the high critical temperature of Nb_3Sn in the removal of steady heat loads to the conductor. (3) The mechanical interaction of the conductor cable and the sheath in a cable-in-conduit conductor is a subtle phenomenon that must be eventually sorted out in order to take advantage of the sheath as a structural component in a coil design. (4) The stability of the cable-in-conduit conductor against external perturbations in a realistic coil environment was demonstrated to be quite high.

PROBLEMS EXPERIENCED IN THE OPERATION OF THE 2 M CRYOSTAT

Too often, only those things that went right in an experiment find their way into a report, and posterity is left with a rosy picture that may be pleasant but unreal. Since tests of the type discussed in this report must be repeated many times in our laboratory in the near future, an account of the problems experienced in the execution of these tests will be very useful. Some of the operational difficulties have been mentioned already in the course of reporting the test results. The following is a more complete list of problems--the kind that would ordinarily be forgotten, at least until the next time they occurred. In most cases I try to suggest a possible prevention for future runs.

Loss of vacuum in cryostat jacket

During cooldown for the October run, vacuum in the 2 m cryostat jacket deteriorated badly (to about 10^{-3} torr). The primary cause was eventually determined to be the feedthru into the vacuum space that delivers LN_2 to the intermediate temperature radiation shield. A soft solder joint to a copper tube constituting the feedthru cracked under thermally induced stresses. The crack was repaired using Wood's metal so as not to make the leak larger while trying to repair it (the system was left under vacuum during the repair). The repair was sufficient for completion of the first test run, but after the test was completed and the line was allowed to warm up, a nearby heater (located there to prevent the freezing of an O-ring seal) melted the Wood's metal and recreated the vacuum leak. Another repair was made, this time with Sn-Pb solder, but it too failed during the January run. This time the line was warmed and the leak repaired with a filled epoxy.

The feedthru design is bad. It should be replaced with a design that utilizes only welded or brazed joints and careful attention should be paid to the relief of thermally induced stresses.

Leak in the LN_2 baffle of the cryostat vacuum system diffusion pump

In the search for the leak just mentioned, a less severe leak was found in the pumping system on the 2 m cryostat vacuum jacket. The LN_2 baffle on the diffusion pump was identified as the source of the problem. The LN_2 reservoir in the baffle had cracked loose from its mechanical supports, either due to vibration or rough treatment during storage or installation, leaving a small leak. The baffle was replaced for these runs with a straight spool piece. The baffle leak was apparently present before the more serious, feedthru leak occurred. For when the system was put back on line after both repairs, the vacuum was an order of magnitude better than before the vacuum failure occurred. However, this "fix" should only be considered temporary and a proper baffle should be replaced in the system.

Failure of shaft seals and belts on cryostat vacuum system fore pump

As is often the case, when a system failure occurs there are more than one or two contributing factors, all masquerading as the major problem. In the search for the problem, it is also unusual to discover all these factors the first time through. The above mentioned vacuum failure is a prime example. In addition to the two leaks already described, it also happened that the foreline vacuum pump failed. Apparently a shaft bearing failed causing a shaft seal to leak and reduce the performance of the pump. The problem was discovered only because the wobbling shaft also caused the drive belts to wear and become loose. All future runs in HFTF should be preceded by a thorough inspection of the various components of the vacuum system. This system is typically run continuously whether the cryostat is in use or not, and components can be on the verge of failure without the operators' knowledge.

Remote JT valve operator malfunction

The Airco refrigerator has remote JT valves for both the 10 kl dewar and for the 2 m cryostat. These have quite different valve operators attached. The positioner on the 10 kl dewar is air operated and that on the 2 m cryostat delivery tube is operated by an electric motor. The motor turns a nut that engages a screw afixed to a shaft. The shaft in turn transmits linear motion to the JT valve needle. To do this, the screw must be constrained from rotating. In the past, this constraint had been provided by means of a projection that also indicated valve position by moving a potentiometer. However, this projection had been removed when the potentiometer had failed in some manner. Since its removal, only the combination of a freely moving nut and a relatively tight shaft seal had provided some measure of rotary/longitudinal motion conversion. The position of the JT valve, recorded as turns of the drive nut, must have been a very imprecisely known quantity under such conditions.

I recommend that the motor driven valve positioner be replaced with an air operated positioner like the one on the 10 kl dewar and that the controls for the two positioners be consolidated.

Malfunction of LN_2 autofill system for Airco precooler/absorber

The autofill system for the precooler/absorber in the Airco refrigerator cold box failed to operate during the October run. We were able to continue by manually filling or stopping when external signs (absence or presence of frost on particular pipes) indicated that the heat exchanger reservoir was either empty or overflowing. However, this procedure resulted in extremely excessive LN_2 consumption, and probably suboptimal cooling at times also. The problem has since been attributed to faulty contacts in a cable connector associated with the level sensors and corrected. The autofill system was operational for the January run.

Freeze-ups of the Airco refrigerator

The 2 m cryostat is an inherently "dirty" system that cannot be completely "cleaned up" no matter how great the effort (the foam plug above the coil stack must contribute greatly to this problem). Thus some "freeze-ups" of the refrigerator cold box, when operating directly into the 2 m cryostat, should be expected. During the January run, however, three turbine failures caused by icing occurred within a period of four days. All the failures occurred after coil temperature was below 100 K, two occurred when the coil temperature was below 60 K. The typical impurities causing freeze-up (air and water) should all have been frozen out in the 2 m cryostat at these temperatures. Some other evidence indicates that the purifiers and not a dirty 2 m cryostat may have been the main problem by allowing impurities (mostly N_2 and O_2) through. Details are sketchy at this time but the performance of these purifiers bears careful investigation before future runs. Frequent freeze-ups may also be avoided by using the Airco only for precooling to around 100 K as suggested earlier, without starting the turbine at all.

Deficiency and failure of He gas recovery compressors

Several times during the October run, and once during the January run, the helium gas recovery bags had to be vented to atmosphere because they overfilled. The recovery compressors had been incapable of keeping up with the boiloff from the 2 m cryostat. In the October run only one compressor was available, the 125 hp Worthington, and it failed during the run. For the January run, the 75 hp Worthington was operational. Both compressors were run continuously to maintain adequate recovery speed. The two together are sufficient, but care must constantly be taken to keep one bag nearly empty, especially during initial filling of the 2 m cryostat when huge quantities of gas are being generated. It is essential that both be operable before a run. Obviously, reducing the cryostat losses would also ease the burden of reliability and of operating at peak performance from these compressors.

Difficulty in rapidly dumping He gas when recovery bags fill

For the October run, the recovery bags could only be dumped manually in the event of and overfill. This resulted in a dangerous situation. In the present configuration, when the recovery bags fill completely, an inlet valve shuts and all gas flow stops, including flow out of the vapor cooled leads, which could easily result in lead burn-out and magnet failure. Before the January run, emergency, electrical operators were installed on the dump valves near the lead flow-meters to allow the operator to act quickly to dump the bags instead of having to run outside to the vent valves in the event of an overfill. In the future, this operation should also be alarmed and automated.

"Malfunction" of JT valve positioner on 10 kl dewar

The pneumatic positioner on the JT valve for the 10 kl dewar is an ancient unit, but still sophisticated and stone- reliable. However, two associated components, a human operator and an instrument-air supply hose, caused minor problems during the October run. Once, the mechanical lever that closes the feedback loop in the pneumatic positioner circuitry was tripped (literally), and once a leak was found in an air supply hose. In both cases the valve and positioner were wrongfully accused of giving deficient service. My advice is, "If the 10 kl JT valve is not working properly for some reason, look elsewhere first."

Loss of vacuum in VJ return from 2 m cryostat to Airco

The vacuum jacketed return line from the 2 m cryostat to the Airco cold box frosted during the October run. No leak was found. The line was pumped overnight with a mechanical pump and put back into service. It would be wise to routinely pump all VJ lines that carry LHe before any extended run.

Unexpectedly high boil off rate in 2 m cryostat

The unduly high consumption of LHe during both the October and January runs has been mentioned already several times. However, I feel the attention is fully warranted. Cryogenic inefficiency is currently the single most serious problem with HFTF because it presents operational difficulties in so many different ways: the losses far exceed our current refrigeration capacity or reasonable expectations of future refrigeration capacity; they deplete our present 14 kl storage capacity in intolerably short periods; the rapid evolution of gas overtaxes our recovery capabilities (possibly also our capablities to maintain gas purity); and since none of the cooling power of this excess boiloff is being utilized, handling of the extremely cold effluent causes problems with maintaining leak tightness of the entire cryostat and recovery system.

The list could go on, but it is already long enough to convince the reasonable person that solutions must be found if HFTF is to be a truly useful tool. I suspect two possible sources of the heat: conduction down the inner wall of the 2 m cryostat has already been alluded to, but the virtual leak of heat slowly being conducted out of the huge foam plug above the coil stack must also be considered. My personal opinion is that the foam plug offers no advantages over a system of baffle plates, and several disadvantages. There is some support in the literature for my opinions, but they are mostly couched in personal experience and the dislike of such a huge source of contamination in a cryogenic system. Metal baffle plates result in a much cleaner system and offer the opportunity of actively controlled cooling by having them traced with a tube, through which a metered flow of cold gas can be extracted (the performance of the plates as a radiation baffle is improved by having a portion of the heat they intercept transmitted to exitting gas rather than liquid in the bath). The boiloff is thereby reduced and the gas that <u>is</u> evolved is warmed in the process to a temperature that makes it easier to handle.

The baffle plates could also be put in good thermal contact with the upper portion of the vessel inner wall to allow much of that conduction heat load to be intercepted also. The opportunity exists to reduce the wall conduction heat load by a factor of 1/35, making it negligible in comparison to the vapor cooled lead losses. The plates could be made economically of aluminum with a tracer tube welded on. Good contact to the vessel wall could be obtained by sectioning the plates to allow them to be cammed out against the cryostat wall after the magnet is lowered in place.

Consideration should also be given to opening the vacuum jacket of the 2 m cryostat and modifying the LN_2 tracer tubing on the shield by providing a section that encircles the inner wall and makes good thermal contact to it at the appropriate distance from the top.

<u>Auxillary fill line impropery positioned in 2 m cryostat</u>

An auxillary fill line was used in the October run to allow LHe transfer initially from several 500 l dewars. The thought was to precool the cryostat with the 500 l dewars and save all the liquid in the 10 kl dewar for a single uninterupted run. The auxillary fill line did not, however, extend deeply enough into the cryostat to guide the flow underneath the coil stack where it was needed for efficient cooling. In fact it was later learned that it did not even extend below the foam plug. In spite of this, some cooling was obtained from the five or so small dewars used, but nothing like their potential cooling capacity was obtained. The importance of knowing the routing of all the various lines penetrating the top plate before lowering the magnet system into the cryostat cannot be over emphasized.

Gas leaks in top of 2 m cryostat

In the January run alone, the gas equivalent of 6000 l of liquid was lost. Much of this loss was due to leaks in the top plate of the 2 m cryostat (predominantly around the vapor cooled leads and in the VCL boxes). The leaks were tolerable before the run, but got much worse during it because of the excessive flow of cold gas associated with the unexpectedly high boiloff rate. Nevertheless, the sources of these leaks must be eliminated by redesign of the lead and lead-box seals before future runs.
A full blown leak test of the low pressure portion of the facility (2 m cryostat and all recovery lines) is also in order. The test could be accomplished while the system is warm by carrying out a pressure decay test extending over several days. Reduction of the liquid consumption in the cryostat will ensure the reliabilty of whatever seal modifications are made by eliminating undue thermal stresses on them.

CONCLUSIONS

The MIT/LLNL 12 T test was extremely useful. The HFTF coil set itself operated faultlessly, unperturbed by the variations of field, temperature, etc. necessary to provide the test environment for the MIT coil inside it. It will be an extremely useful tool for future such testing, unduplicated in many ways, anywhere else in the world. The operations crew also gained experience that will be invaluable in future testing. In general, the entire facility, including the cryogenic system, is excellent; but there are many details that can be, and for efficient operation must be, corrected.

FIGURE CAPTIONS

Figure 1. Cannister for containing the MIT 12 T coil inside HFTF.

Figure 2. Elevation view showing the MIT 12 T coil and the cryogenic package in HFTF.

Figure 3. Schematic of the flow circuit of the MIT 12 T coil and the cryogenic package inside the 2 m cryostat.

Figure 4. Schematic of the flow measurement/control panel located outside the 2 m cryostat.

Figure 5. Record of the cooldown of the HFTF/MIT coil assembly for the October run.

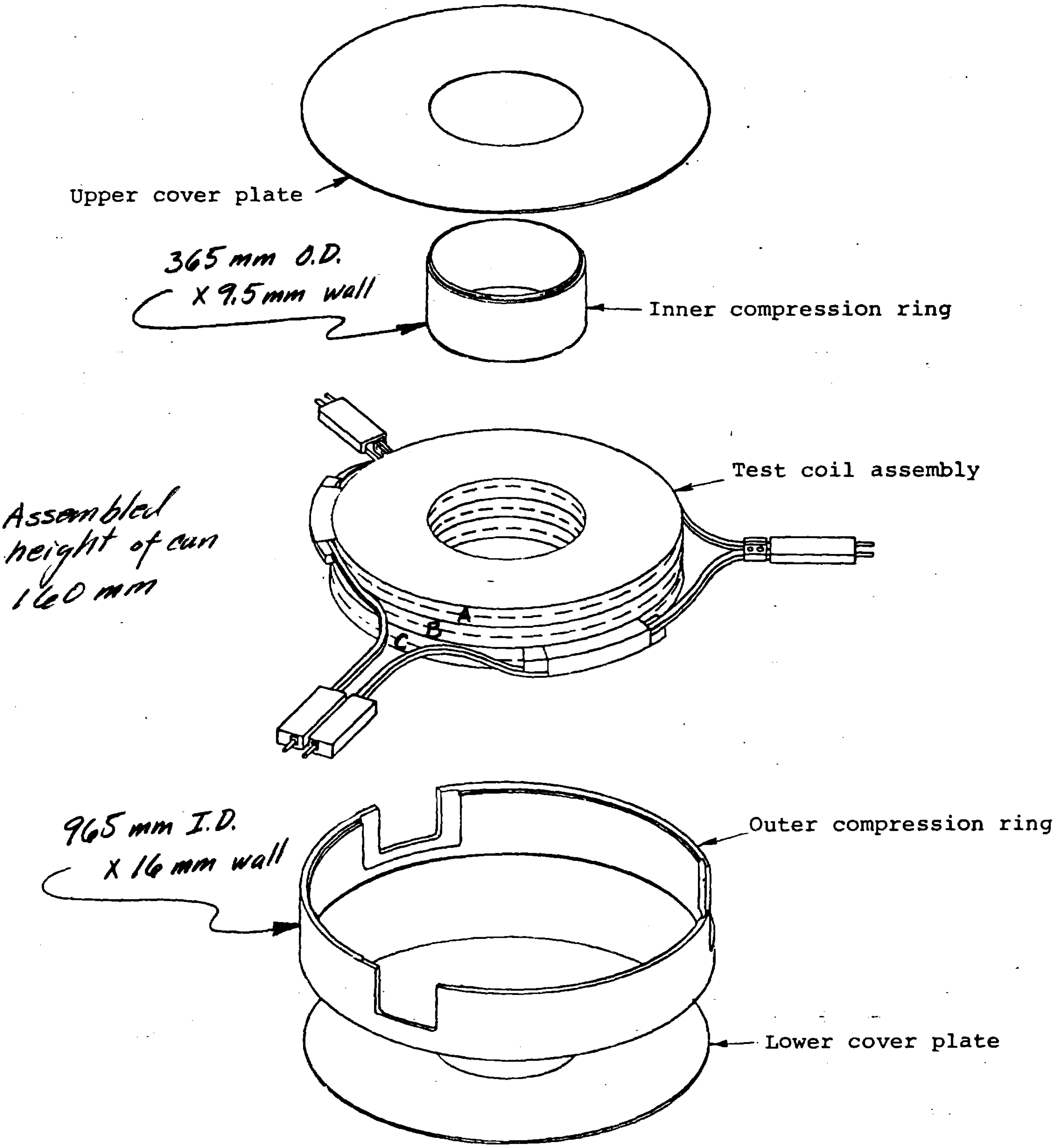
Figure 6. Record of the cooldown for the January run (first six days).

Figure 7. Record of the cooldown for the January run (continuation).

Figure 8. Estimated volume of LHe in the 2 m cryostat vs. indicated level.

Figure 9. Measured standby boil-off rate vs. level in the upper range. The cryostat was previously full.

Figure 10. Measured standby boil-off rate vs. level in the lower range. The cryostat was previously full.



Exploded assembly of test coil and coil case.

Figure 1.

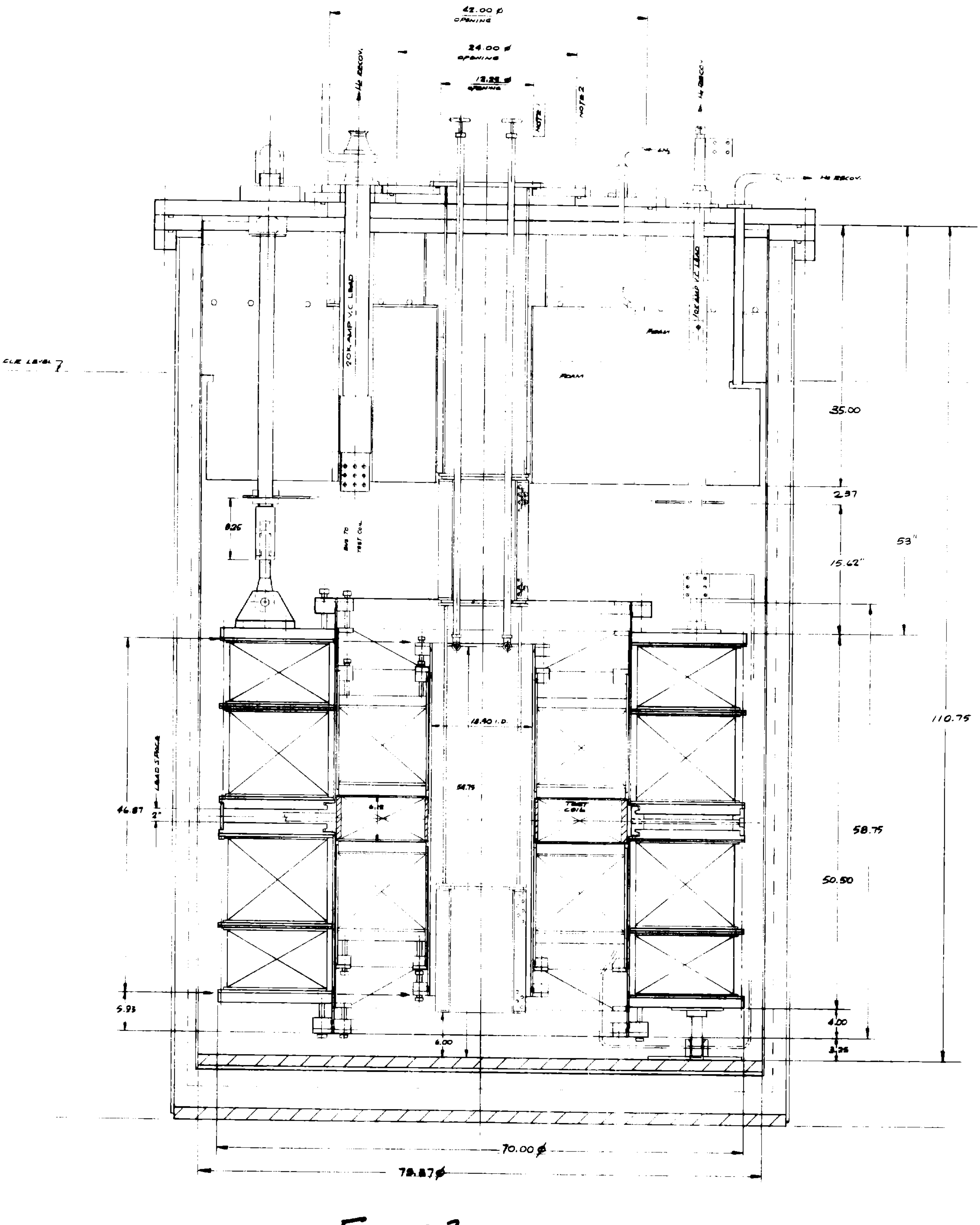
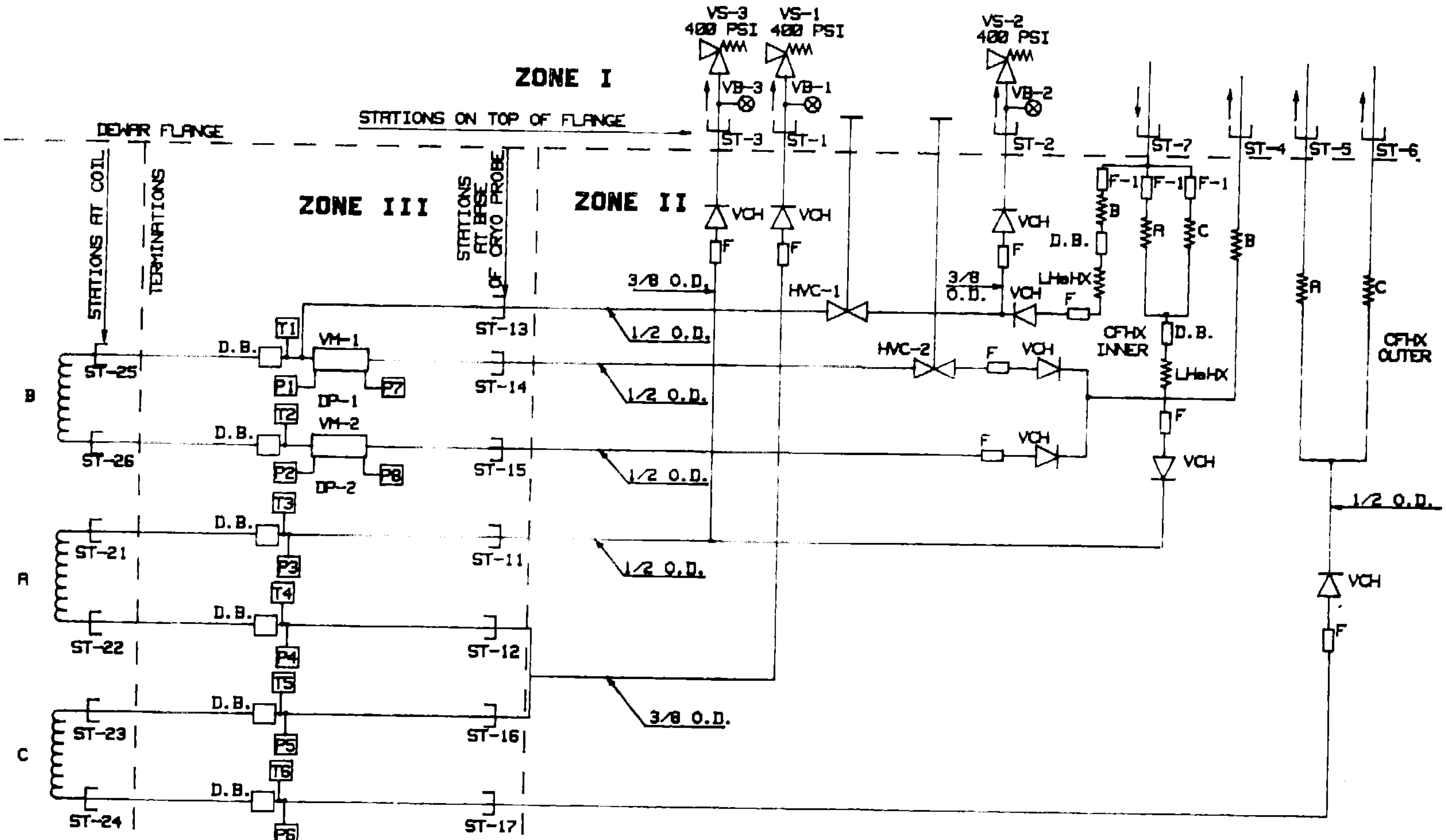

42.00 ⌀
OPENING
24.00 ⌀
OPENING
20K AMP V.C LEAD
FOAM
35.00
53"
15.62"
110.75
58.75
50.50
46.87
2"
5.93
4.00
6.00
70.00⌀

Figure 2.



12T--TEST COIL SCHEMATIC

Figure 3.

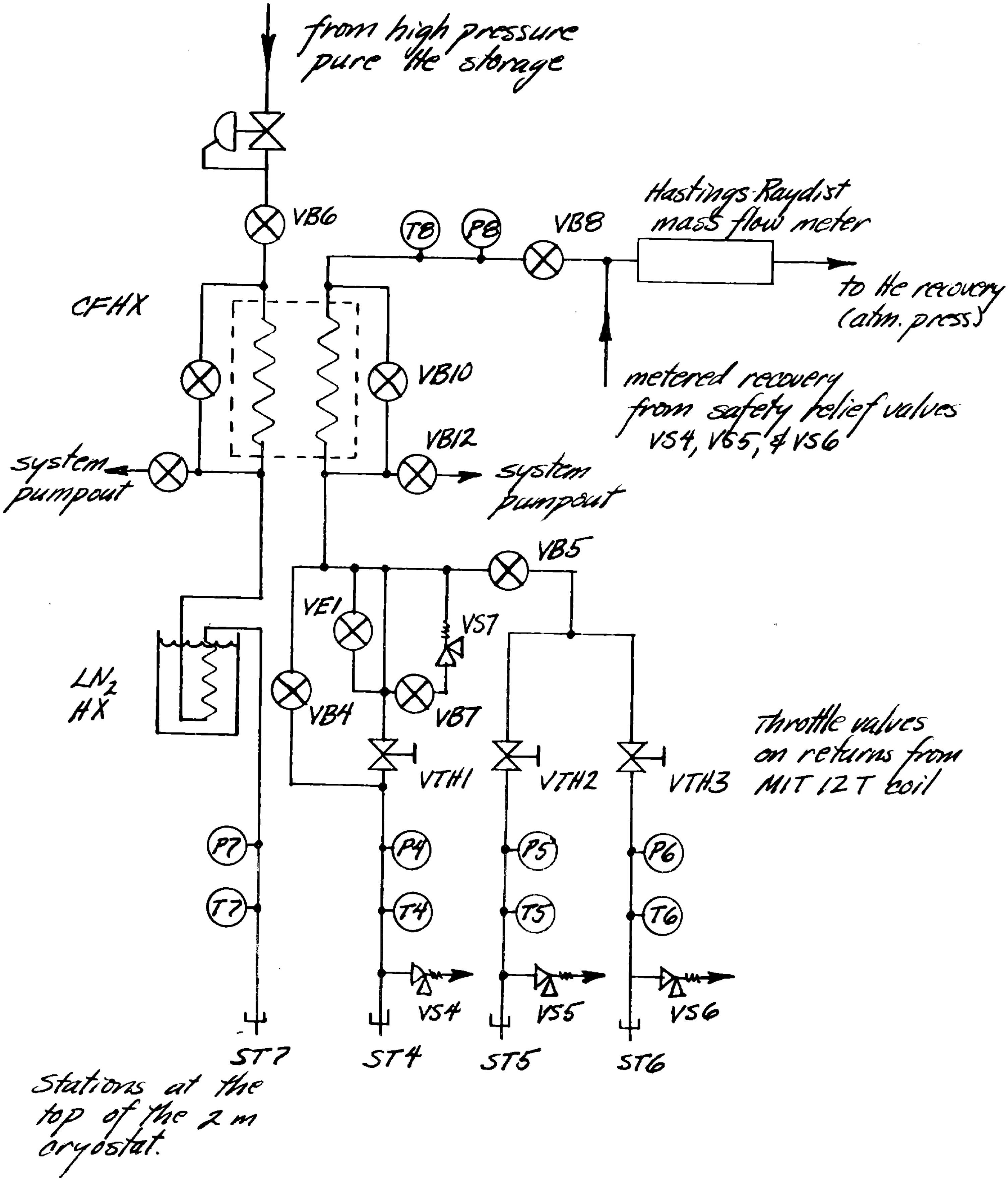

from high pressure pure He storage
VB6
T8
P8
VB8
Hastings-Raydist mass flow meter
to He recovery (atm. press)
CFHX
VB10
metered recovery from safety relief valves VS4, VS5, & VS6
VB12
system pumpout
system pumpout
VB5
VE1
VS7
LN2 HX
VB4
VB7
Throttle valves on returns from MIT 12 T coil
VTH1
VTH2
VTH3
P7
P4
P5
P6
T7
T4
T5
T6
VS4
VS5
VS6
ST7
ST4
ST5
ST6
Stations at the top of the 2 m cryostat.

Figure 4.

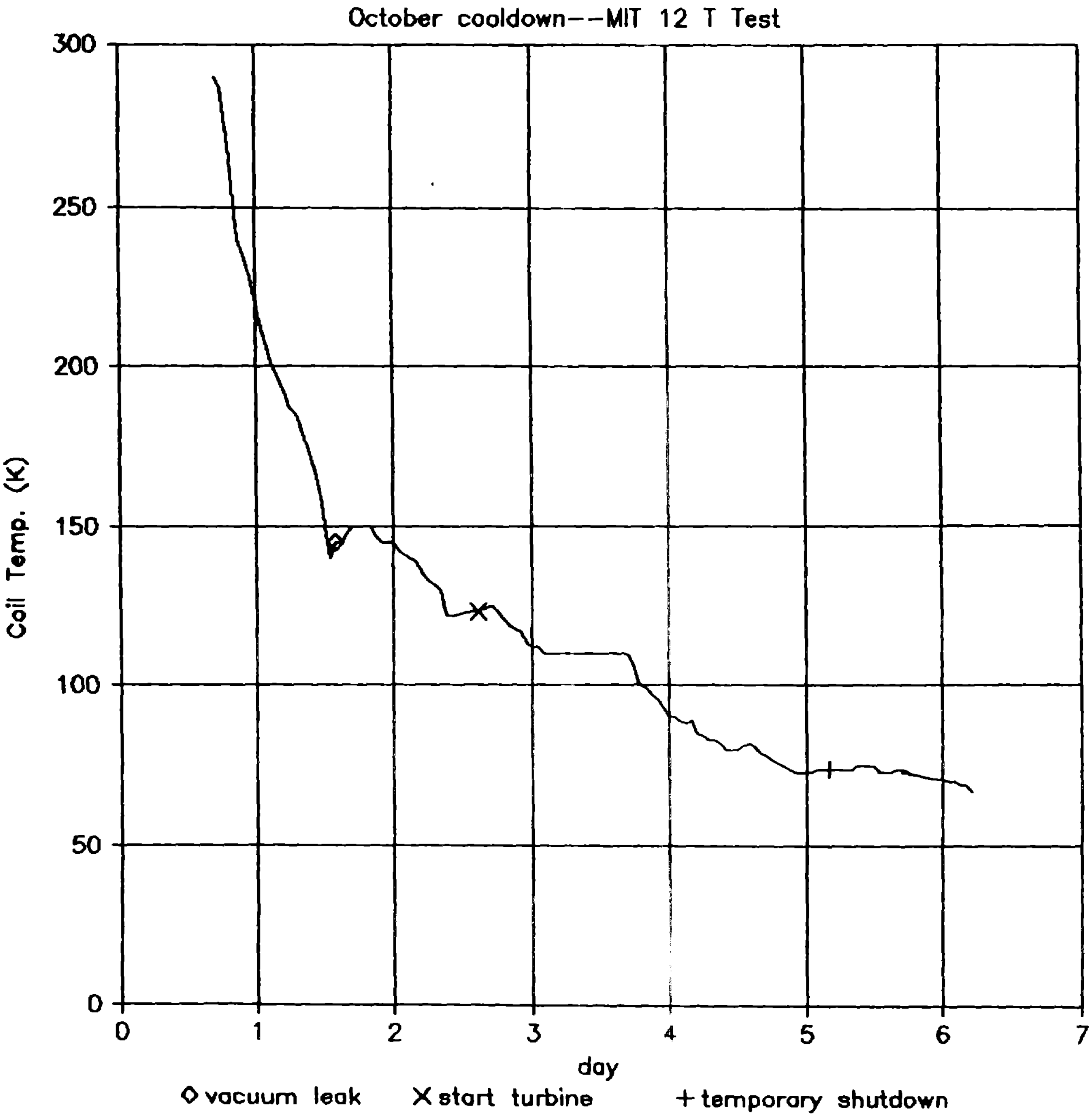

October cooldown--MIT 12 T Test
Coil Temp. (K)
300
250
200
150
100
50
0
0
1
2
3
4
5
6
7
day
◇ vacuum leak
X start turbine
+ temporary shutdown

Figure 5.

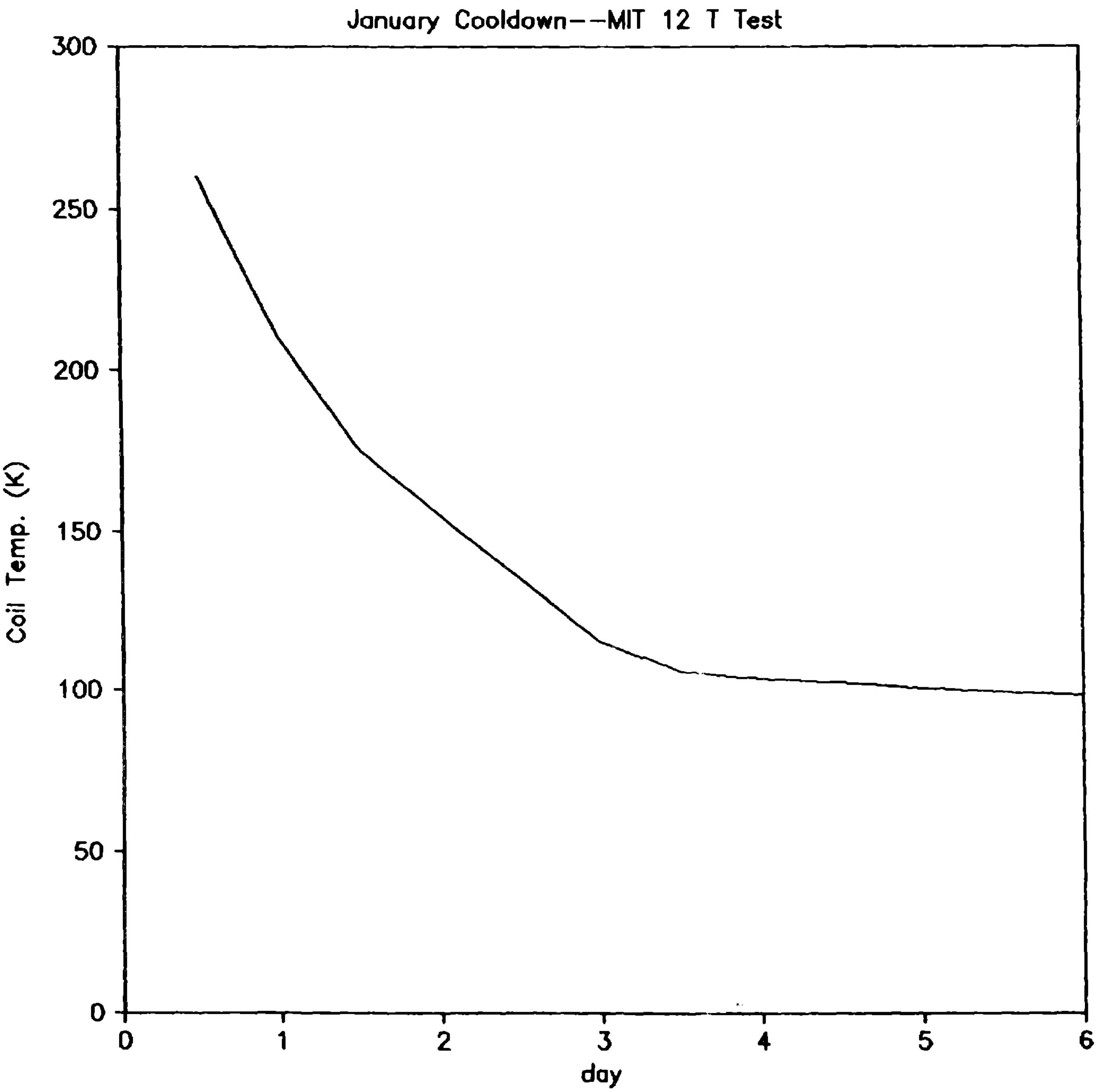

January Cooldown--MIT 12 T Test
Coil Temp. (K)
300
250
200
150
100
50
0
0
1
2
3
4
5
6
day

Figure 6.

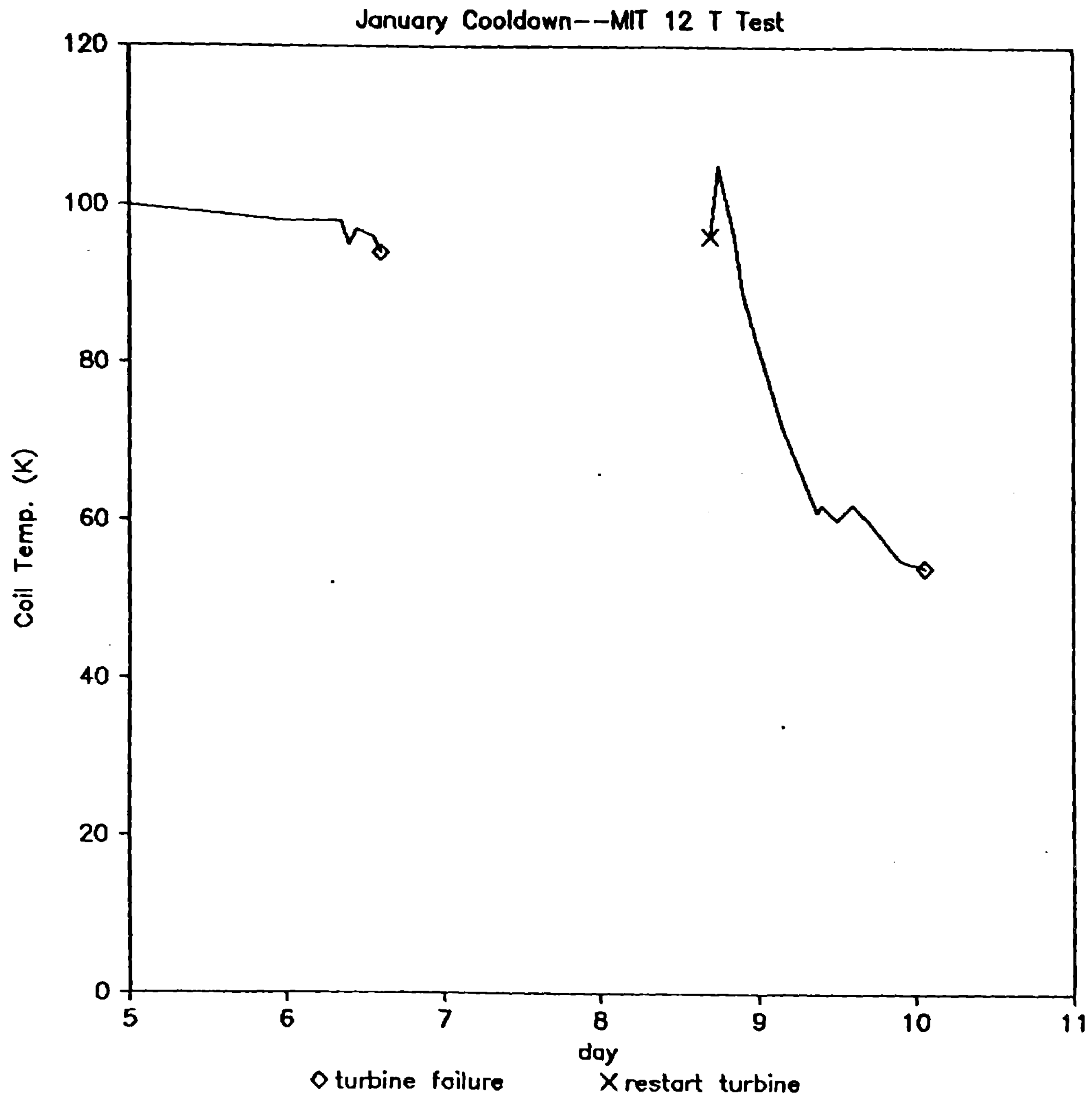
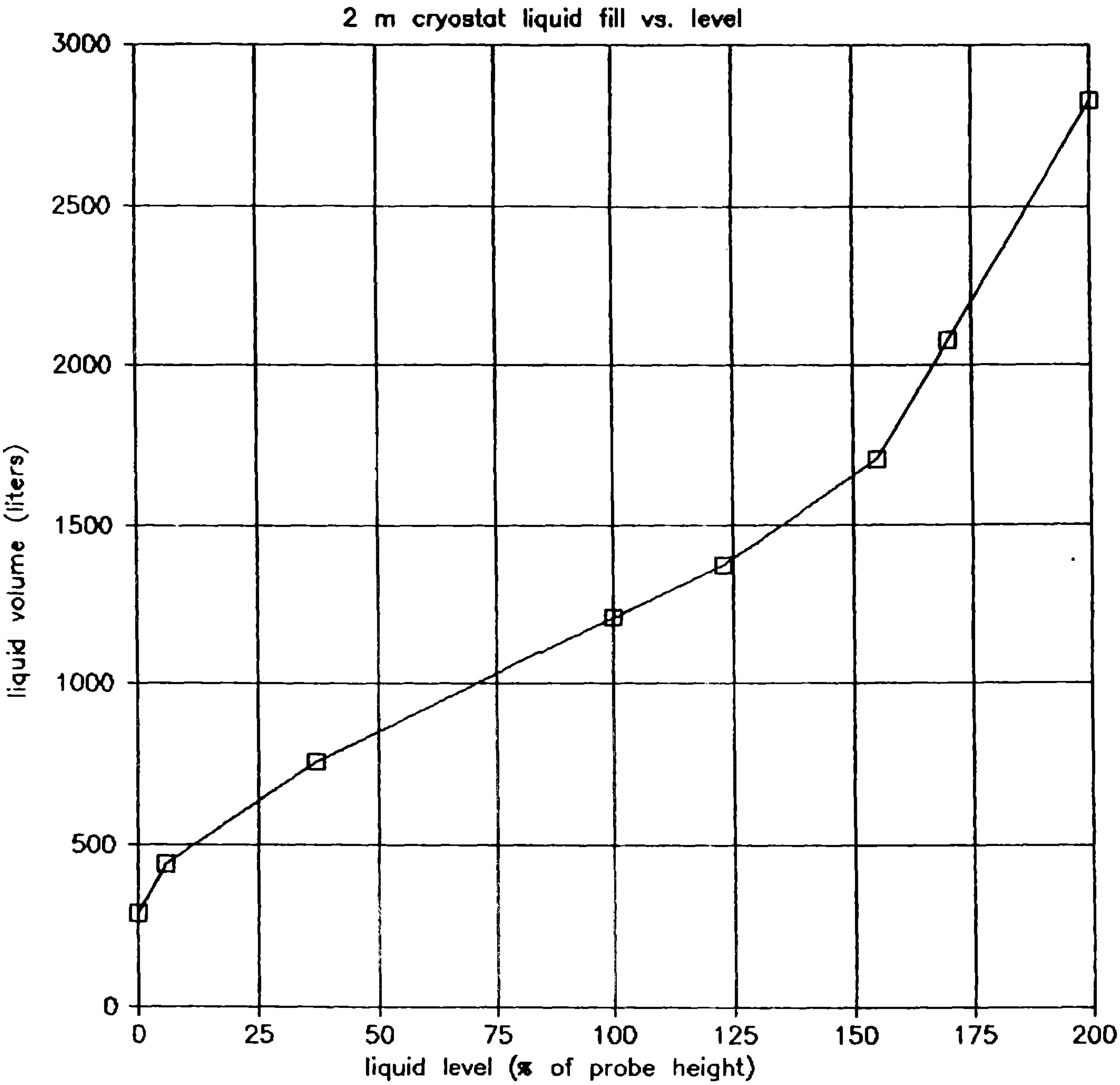
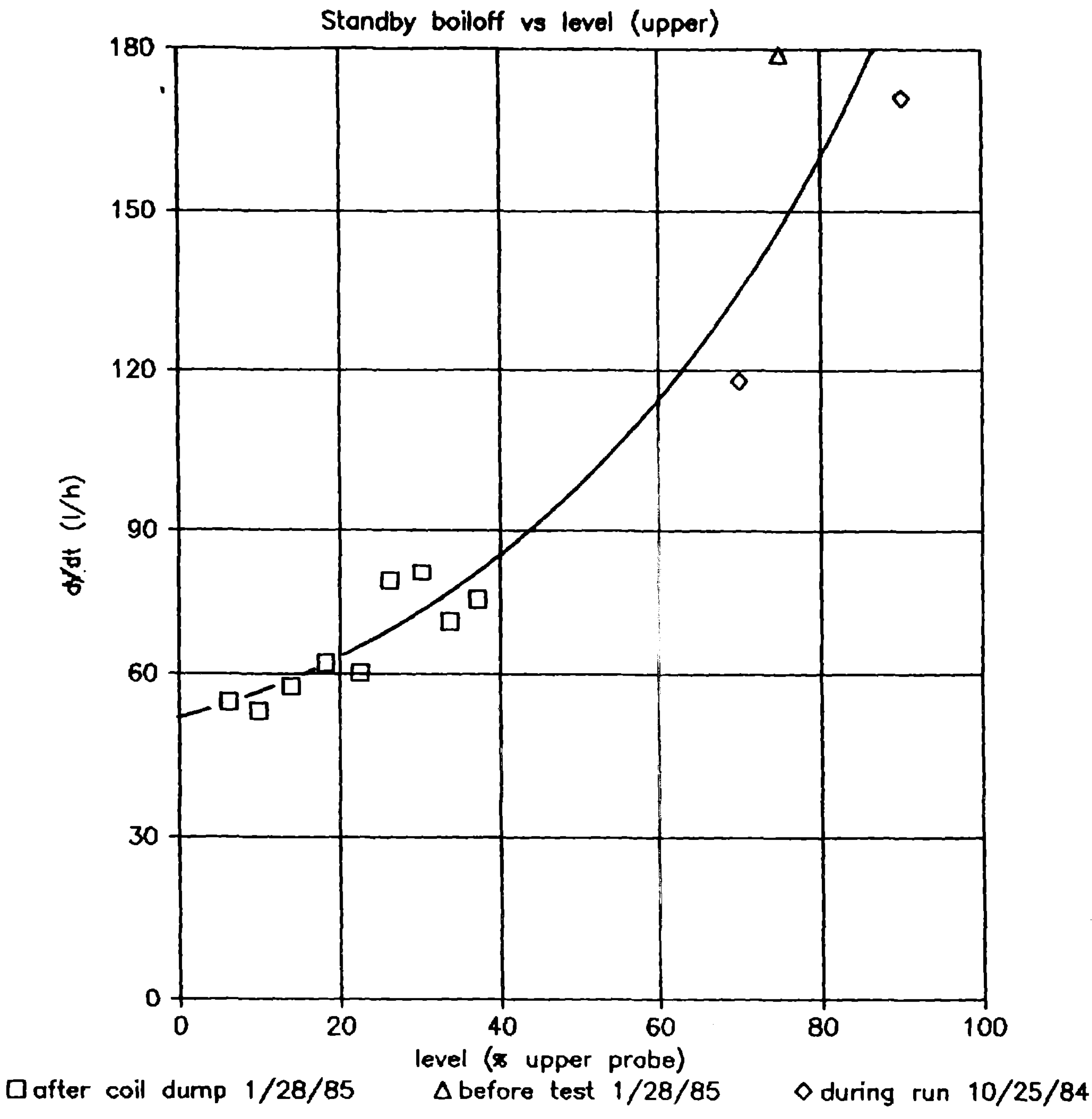

January Cooldown--MIT 12 T Test
120
100
80
60
40
20
0
Coil Temp. (K)
5
6
7
8
9
10
11
day
◇ turbine failure
X restart turbine

Figure 7.



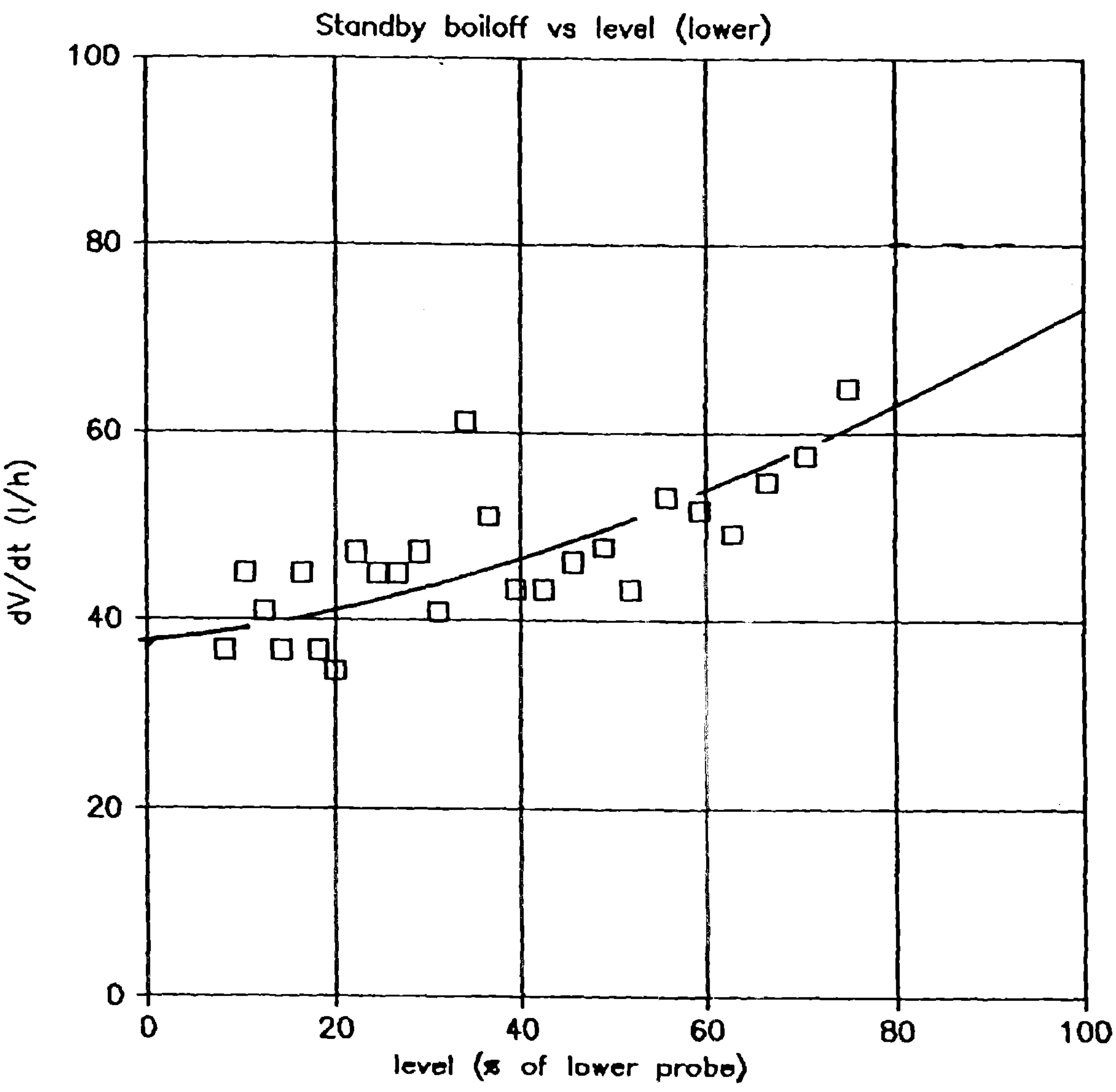
2 m cryostat liquid fill vs. level
3000
2500
2000
1500
1000
500
0
liquid volume (liters)
0
25
50
75
100
125
150
175
200
liquid level (% of probe height)

Figure 8.



Standby boiloff vs level (upper)
180
150
120
90
60
30
0
dV/dt (l/h)
0
20
40
60
80
100
level (% upper probe)
□ after coil dump 1/28/85
Δ before test 1/28/85
◇ during run 10/25/84

Figure 9.



Standby boiloff vs level (lower)
100
80
60
40
20
0
dV/dt (l/h)
0
20
40
60
80
100
level (% of lower probe)

Figure 10.

APPENDIX A

MIT Preliminary Test Report

November 19, 1984

Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

PHASE I EXPERIMENTAL RESULTS
MIT 12T TEST COIL

Mitchell O. Hoenig , leader
Superconducting Magnet Development Group.

SUMMARY

Critical current (I_c)tests of the MIT-12T-Coil at LLNL in the HFTF facility were performed on October 30th 1984. A peak field of 12 teslas was attained with a critical current of 17,000 amps. Critical current densities (Jc) of 254.5 and 284 .4 A/mm^{2}of non-Cu were measured at an electrical sensitivity of 0.03 µV/cm and a temperature of 4.2K at peak fields of 11.9 and 11.5 teslas (respectively) for the 486 strand bronze matrix Nb_3Sn ICCS conductor sheathed in JBK75.

INTRODUCTION

The 12 T MIT Test Coil is a 1m diameter test coil which consists of three 39 m lengths of Internally Cooled Cabled Superconductor (ICCS), wound in the form of three double pancakes. It has been installed in the 9T background field High Field Test Facility (HFTF) at the Lawrence Livermore National Laboratory (LLNL). The ICCS conductor in the MIT coil is a 486 strand bronze matrix Nb_3Sn cable, encapsulated in a JBK-75 tube with a 32% helium space, reacted at 700C for 4 days followed by 2 days at 730C. Initial tests of the coil, performed on October 30th and described below have demonstrated a 12 tesla peak field at a critical current of 17,000 amperes measured at a 0.03 µV/cm sensitivity .

The coil was wound at the Everson Electric Co. prior to reaction using the Westinghouse Large Coil ICCS conductor fabricated by Oxford/Airco. After activation the coil's three double-pancakes were insulated with G-10 strips and were vacuum impregnated with epoxy. The subcoils were then assembled in a steel casing , later installed in the HFTF.

TEST ASSEMBLY

An elevation view of the magnet assembly is shown in Figure 1, conductor geometry in Fig. 2.

PHASE I TESTS

A preliminary zero-background-field test as well as Critical Current and Steady State tests were performed on the MIT 12T Test Coil in the HFTF background field test facility at LLNL during the last two weeks of October 1984.

With the HFTF inactive, the MIT Coil current was ramped up to 19,000 amps, raising peak field from zero to approximately 3 teslas. Measurements of subcoil termination joint resistances were simultaneously recorded (see Table I)

Three Critical Current tests were performed. Test 1 was exploratory. Test 2 was designed to determine peak critical current (Jc) at or close to 12 T. Test 3 was designed to determine peak field at a critical current of 19,000 amps, the limit of the available power supply

<u>Test 1.</u> The HFTF was brought to its maximum field of 9.1 T.
The MIT coil current was then brought up to 15,000 A in 1000 A increments
While no quench occured it was not possible to observe current sharing voltages. The test was thus terminated by ramping the MIT coil current down to zero
Neither the peak current attained, nor subsequent MIT coil current ramp-down caused a quench of the HFTF coils.

<u>Test 2.</u> With the HFTF generated field still at 9.1 T the MIT coil current was brought up from zero at a steady ramp rate of approximately 1500 A per minute.

The current was then ramped down to zero on a verbal order when at 17,000 A a current sharing voltage of 3.4 µV ,(corresponding to 0.026 µV/cm) was observed on the Voltage vs Current (X-Y) recorder.

Neither the peak current attained, nor subsequent MIT coil current ramp-down caused a quench of the HFTF coils.

Fig 3 shows the plot of CURRENT vs FIELD as well as CURRENT vs ELECTRIC SENSITIVITY (expressed in µV/m).

Fig 4 shows the LOAD LINE plot for the MIT Test Coil.

Lap joint resistances, measured on the MIT Coil lead and joint terminations are shown in Table I.

Test 3

The HFTF generated field was reduced to 8.5 T.

With a background field of 8.5 T the MIT coil current was ramped up at a steady rate of (approx.) 1500 A/min.

The current was again ramped down to zero on a verbal order when , at 19,000 amps and a Hall Probe indicated peak field of 11.5 T. A current sharing voltage of 3.3 µV (corresponding to 0.025 µV/cm) was reached.

Again the HFTF coils did not quench.

Test results are shown in Figs 3 & 4.

Steady State Test.

With the HFTF providing a background field of 9.1 T the MIT coil current was brought up to 15,000 amps, providing a field of 11 T.

The current and field were maintained at this level for a period of 300 seconds.

Carbon-glass temperature monitors located in the helium stream,(between subcoils) indicated no rise in temperature.

Non-inductive voltages of ≤ 0.7 µV were measured accross the peak field portion of each subcoil, corresponding to an electrical sensitivity of ≤0.005 µV/cm.

The 20,000 A power supply, operating at a total current of 15,900 A showed signs of overheating during the steady state test ,which was thus limited to 5 minutes.

TABLE I MIT SUBCOIL LAP JOINT RESISTANCES

JOINT	RESISTANCE HFTF OFF (B @ joint negl.)	RESISTANCE HFTF ON (B @ joint approx. 1.5T)
A LEAD	25 nΩ	33 nΩ
C LEAD	9 nΩ	9 nΩ
A-B Joint *	53 nΩ	69/79 nΩ
B-C Joint	13 nΩ	16 nΩ

Note *..........Relatively high resistance of the A-B joint could have been caused when the coil was inadvertantly dropped on the joint during assembly.

PRELIMINARY CONCLUSIONS, PHASE I.

As can be seen in Figs 3 and 4, Critical Currents of 17,000 and 19.000 Amps have been measured at fields of 11.9 and 11.5 T (resp.) at electrical sensitivities of 0.06 µV/cm. These results correspond to current densities (J_c) in the non-copper portion of the wire equal to 72.5 % of current densities in "unstrained" single strands of wire reacted under identical conditions and compare favorably with subsize (27 strand) short-sample tests [1]. The 27.5 % reduction in J_c is due to strain caused by the differential thermal contraction between the superconductor and its JBK75 sheath, following reaction.

Joint resistances measured are high, (see Table I, above). They are 10 times higher than resistances measured during component tests [2].

CREDITS

Experimantal work on the MIT Test Coil is being performed jointly by LLNL and MIT's Plasma Fusion Center under DOE sponsorship. Principal experimentalists are John Miller (LLNL) and Mitchell Hoenig, Michael Steeves and Joe Minervini (MIT). The JBK75 sheathed ICCS conductor was manufactured by Oxford - Airco and is identical to the Westinghouse LCP Coil conductor. It was furnished to MIT by ORNL. The 12T Test Coil was wound and insulated at the Everson Electric Co., Bethlehem, Pa. The coil was designed by MIT and was installed in the HFTF Facility by LLNL.

COMMENT

Phase II of the test program will be resumed as soon as the test coil and its hydraulic system can be pressurized. It appears that leaks in welds external to the coil assembly have opened up , causing a substantial helium leak. The welds have been repaired and are being leak tested in preparation for Phase II tests. Phase II tests will include Critical Current tests at elevated temperature (4.2 to 10K), Stability Margin measurements, Quench Propagation tests and the measurement of peak helium pressure following quench. An attempt will also be made to repeat Critical Current measurements at 4.2K at higher electric sensitivities, of up to 200 μV (1.5μV/cm compared to the 0.026 μV/cm used as critical current criteria in Phase I tests) .

Definitive conclusions should not be drawn from test results reported above. A thorough test analysis as well as review of all measurements is in progress. A final test report will be issued in due course.

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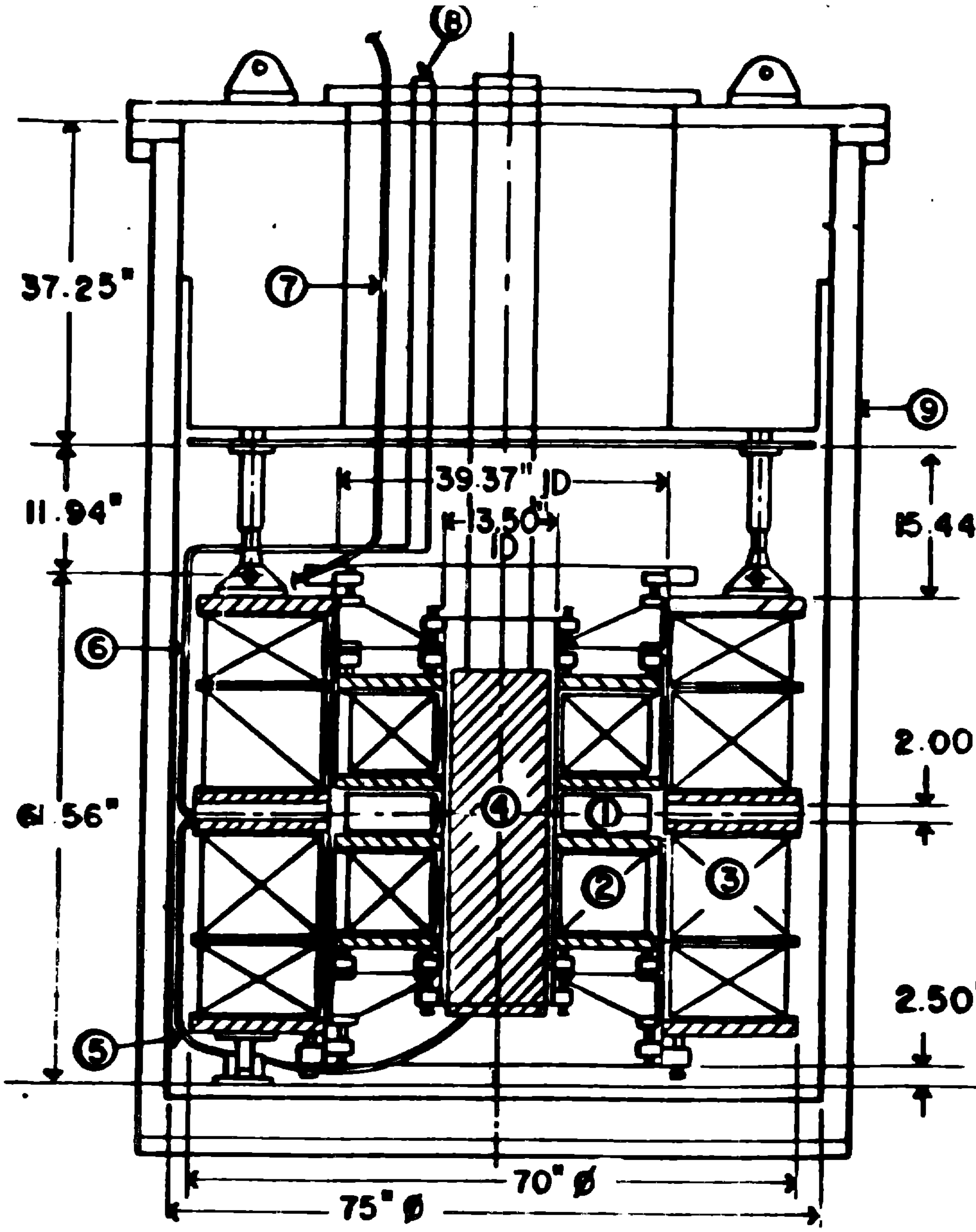
1. M.O.Hoenig, M.M.Steeves and C.J.Cyders, "Niobium-3-Tin ICCS Technology II". 8th International Conference on Magnet Technology (MT8), Grenoble, France, September 1983; Journal de Physique, Colloque C1, pp 599-602.

2. M.M.Steeves and M.O.Hoenig, "Lap Joint Resistance of Nb_3Sn Cable Terminations for the ICCS-HFTF 12 Tesla Coil Program" IEEE Trans. Magn., Vol. MAG-19, pp. 378-381, May 1983.



(1) MIT 12 TESLA TEST COIL
(2) HFTF Nb_3Sn END PLUGS
(3) HFTF NbTi BACKGROUND FIELD COIL
(4) MIT CRYOGENIC PACKAGE INCLUDING HEAT EXCHANGERS AND CRYOGENIC VALVES.(Safety-Relief valves not shown)

(5) HYDRAULIC CONNECTIONS BETWEEN MIT 12 T SUBCOILS
(6) SUPERCONDUCTING BUS BARS
(7) PULSE COIL LEADS
(8) 20,000 AMP CURRENT LEADS

FIG 1 LLNL's HFTF COIL WITH MIT's 12T-TEST- COIL

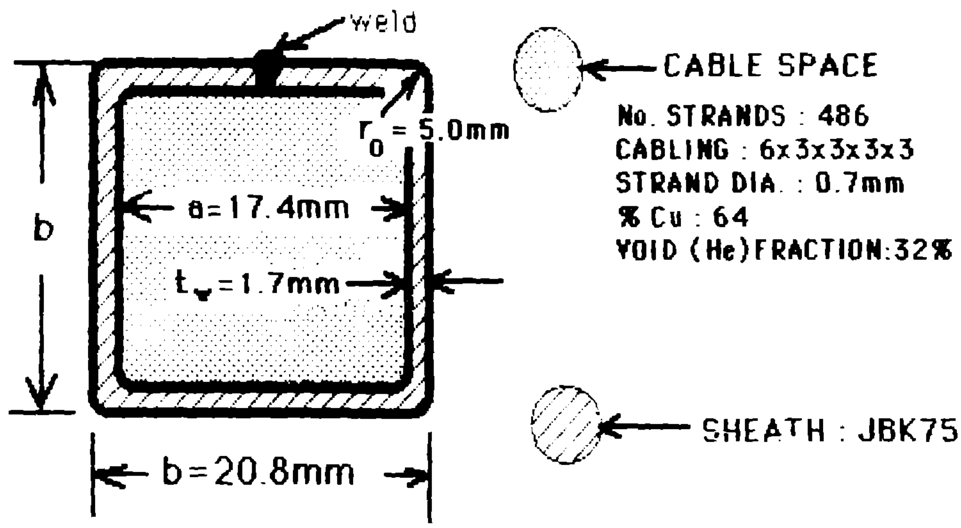
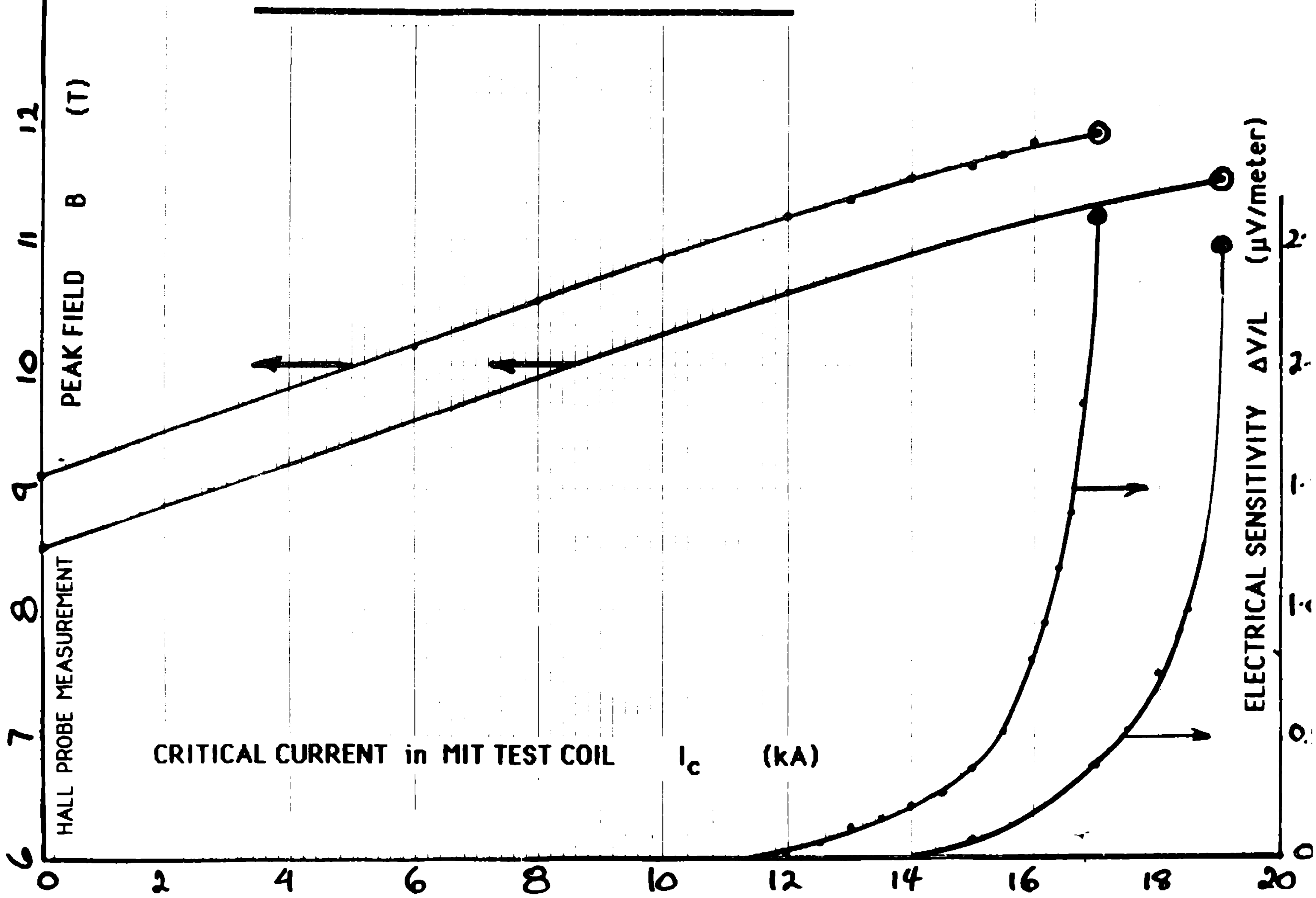


FIG 2. MIT 12T TEST COIL ICCS GEOMETRY

FIG 3 B vs I AND ΔV/L vs I



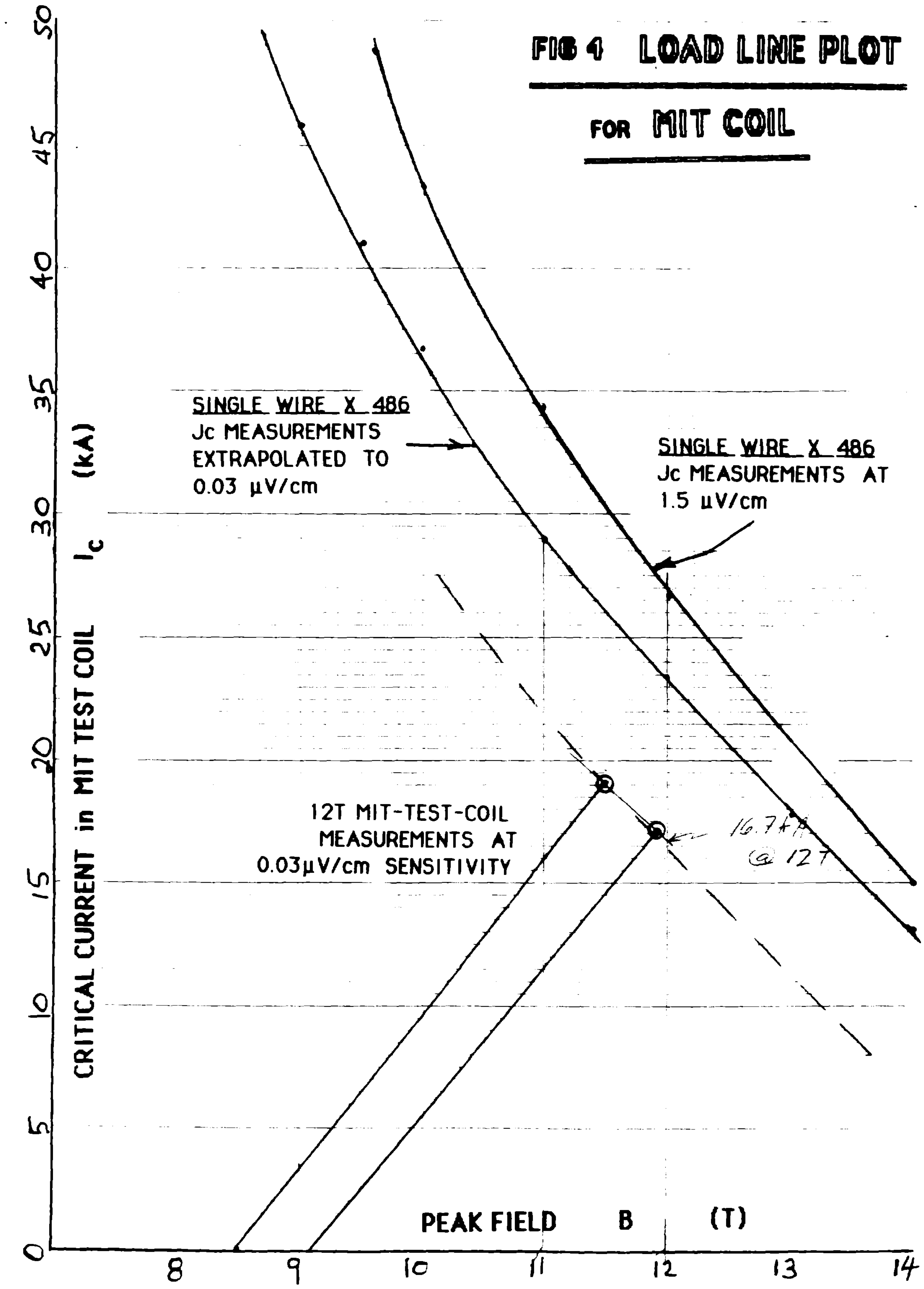


FIG 4 LOAD LINE PLOT
FOR MIT COIL
SINGLE WIRE X 486
Jc MEASUREMENTS EXTRAPOLATED TO 0.03 µV/cm
SINGLE WIRE X 486
Jc MEASUREMENTS AT 1.5 µV/cm
12T MIT-TEST-COIL MEASUREMENTS AT 0.03µV/cm SENSITIVITY
16.7kA @ 12T
CRITICAL CURRENT in MIT TEST COIL I_c (kA)
PEAK FIELD B (T)
0
5
10
15
20
25
30
35
40
45
50
8
9
10
11
12
13
14

APPENDIX B

Comments on the MIT Preliminary Test Report

Lawrence Livermore National Laboratory

December 7, 1984

Dr. Mitchell O. Hoenig, Leader
Superconducting Magnet Development Group
MIT Plasma Fusion Center
167 Albany Street
Cambridge, Massachusetts

Dear Mitch,

Thanks for the copy of the test report (Memo, Hoenig to Der, 11/19/84). It is very complete, and I think the results are very interesting, especially regarding the effect of the cool-down strain degradation on real, full size ICCS conductors. I have enclosed an Attachment with my comments on what I think are the implications of these results. Please let me know your reactions.

There are two minor quibbles I have with details in your report. First, the item of lap joint resistances. You "starred" the A-B joint and alluded to possible causes. I think your basis for singling out that joint is weak. The joint, in fact, constitutes two joints, i.e., superconductor in one pancake to copper and copper back to superconductor in another pancake. At 53 nΩ this double joint is, within measurement error, exactly twice the resistance of the single joint at A. Thus, it is improper to say it is worse than all others.

Second, it was clearly determined that the leaks that caused shut-down of testing were in fact, glass-filled Teflon seals in the bonnets of two cryogenic valves in the cryogenic package supplied by MIT. These seals have since been removed with great expenditure of time and effort by the LLNL crew and the bonnets welded tight. This repair was adopted because we had no assurance for the leak tightness of the teflon seals during a subsequent cool-down.

All in all, I think the initial pay-off from our testing has been fruitful. The results have been enlightening and performance of the system is encouraging that we will be able to successfully complete all planned phases of testing. With consideration for time required for repairs and the upcoming holidays, we should be testing again the third week in January.

Best wishes,

John R. Miller
Superconducting Magnet Development Group
Magnetic Fusion Engineering Division

JRM:jv

cc: E. Dalder, LLNL
M. Lubell, ORNL
B. Montgomery, MIT
M. Steeves, MIT
V. Der, DOE

Attachment A. Comments on the MIT/LLNL 12T Test Results (Memo, Hoenig to Der, 11/19/84).

The MIT/LLNL 12T test adds needed information to the data base interactions between sheath and cable in an I.C.C.S.. There are some minor discrepancies in the preliminary report which I will avoid by referring for my point only to Fig. 4 which I have reproduced here as Fig. 1. From the figure, the critical currents for the test coil at the 0.03 V/cm level are set at 19 kA at 11.5 T and 17 kA at 11.9 T which extrapolates to 16.5 kA at 12 T. Also reported on the same figure are "single strand" critical currents at the same sensitivity for strands "reacted under identical conditions." That curve gives a critical current of 23.4 kA at 12 T. We know that single strands are under residual pre-compression due to differential cool down strains of the copper and bronze vs. the Nb_3Sn. I used the values in Table 1 for computing the expected residual compressive strain to be -0.0019, assuming the bronze and copper yield. Then I used Ekin's formulation[1] to calculate normalized critical current vs. total filament strain appropriate for the conductor at hand to allow conversion of the "single strand" number to "maximum" critical current of 24.95 kA. There is not a great deal of difference between my calculations as represented in Fig. 2 and those presented elsewhere, but I do want to emphasize that this curve was calculated by paying strict attention to detail and using values appropriate for this conductor wherever possible. B_{c20} was obtained from a Kramer plot of Airco J_c vs. B data and T_{c0} was obtained by linear fit to a broad range of Airco J_c vs. T data, (nominally the same strands as in these cables).[2,3] In this fashion the MIT/LLNL test value is found to correspond to:

$$\frac{I_c}{I_{cm}} = 0.67$$

Obviously the test value is degraded by differential cool-down strains imposed by the sheath, but the <u>amount</u> of degradation is the interesting thing. If the mechanical link between sheath and cable strands had been completely rigid, the conductor parameters in Table I and the formula for cool-down strain,[4,5]

$$\epsilon_{fil} = \frac{E_{sh} A_{sh}\left[\left(\frac{\Delta L}{L}\right)_{sh} - \left(\frac{\Delta L}{L}\right)_{fil}\right] - \left(\sigma_{cu,y} A_{cu} + \sigma_{bz,y} A_{bz}\right)}{E_{sh} A_{sh} + E_{fil} A_{fil}} \qquad (1)$$

would have given a predicted residual strain of -0.0089. From Fig. 2 we would have I_c/I_{cm} = 0.223 or I_c = 5.6KA, one third of the observed value. Obviously the sheath cool-down strain is not transmitted directly to the cable. This fact must be recognized and carefully considered in selecting the sheath material and the cable configuration for an ICCS, because it is at least qualitative confirmation of what already has been observed on short sample tests; void fraction affects cool-down pre-strain.[4,5,6]

A simple minded model that may prove useful in characterizing this effect in the ICCS conductor system is shown schematically in Fig. 3. According to this scheme, Eq. (1) for filament cool-down strain should be replaced by,

$$\epsilon_{fil} = \frac{E_{sh}A_{sh}\left[\left(\frac{\Delta L}{L}\right)_{sh} - \left(\frac{\Delta L}{L}\right)_{fil}\right] - \left(\sigma_{cu,y}A_{cu} + \sigma_{bz,y}A_{bz}\right)\left(1 + \frac{E_{sh}A_{sh}}{E_{cs}A_{cs}}\right)}{\left[E_{sh}A_{sh} + E_{fil}A_{fil}\left(1 + \frac{E_{sh}A_{sh}}{E_{cs}A_{cs}}\right)\right]}$$

which differs from Eq. (1) only by the appearance of the factor

$\left(1 + \frac{E_{sh}A_{sh}}{E_{cs}A_{cs}}\right)$ in certain terms. Here E_{cs} is some "effective modulus" for the link between sheath and cable. Also, I have arbitrarily assigned to the cross section of this hypothetical link, the area of the cable space A_{cs}. I would expect E_{cs} to vary with void fraction becoming essentially infinite as void drops to zero and falling to small values (although probably never negligible for any practical conductor) as void fraction is increased.

What other insight can be taken from this model? Let's look at the magnetically induced strain increment $\Delta\epsilon_{fil}$ if this conductor system is used in the windings of a solenoid. According to the model, the magnetic strain is

$$\Delta\epsilon_{fil} = \frac{IBR}{E_{sh}A_{sh}}\left(1 + \frac{E_{sh}A_{sh}}{E_{cs}A_{cs}}\right),$$

which gives the intuitively obvious result that magnetic strain will be higher for cables with finite void, (E_{cs} finite), at least for small strains. Actually I expect this model to apply only for small incremental strains. At some point the sheath must be effective in restraining the cable. I feel it is imperative to determine the applicability of this model, and if it is applicable, the range of applicability. Reliable design with the ICCS conductor depends on its strain behavior.

While thinking about this issue, I have turned up some other data that appears consistent with my model. Airco had tensile tests of the "Westinghouse subsize" conductors done at LLNL some years back.[7] The conductors were longer than the MIT, 27 strand samples, and careful attempts were made to pin the cable ends to the sheath preventing longitudinal slippage. The results are presented in Figure 4. The data epresent a very similar conductor at the same field. It is obvious that this curve is qualitatively different from Fig. 2; the dependence on strain is not as steep. From the model of Fig. 3, we find that incremental strain induced on a conductor by pulling directly on the sheath (the only accessible part) is given by

$$\Delta\epsilon_{fil} = \frac{\Delta\epsilon_{sh}}{\left[1 + \frac{(E_{cu}A_{cu} + E_{bz}A_{bz} + E_{fil}A_{fil})}{E_{cs}A_{cs}}\right]}.$$

The change in critical current from initial value to maximum should correspond to a degradation due to residual cool-down strain. From Fig. 2, the amount of degradation relieved by pulling the conductor should correspond to removing a total initial conductor strain of -0.0046. However, the amount of strain applied to the sheath to accomplish this was 0.0073. It should be noted that the conductor parameters, i.e., void fraction and proportions of materials, are very similar to those for the MIT/LLNL 12 T test and the indicated prestrains are also very close.

To conclude on this point, may I reiterate that the critical currents observed in the MIT/LLNL 12 T test give qualitative confirmation in long conductors of the effects of void fraction on prestrain already observed in many short samples. It is of the utmost importance to finish sorting out this effect and to examine its ramifications. Indications are that the ICCS conductor must be thought of as a conductor system, and its components cannot be chosen based on individual properties without consideration for those of the others. On the other hand, we are very close to having the understanding we need to make our choices wisely.

TABLE I. Conductor mechanical parameters for the MIT/LLNL 12T test.

$$E_{fil} = 165 \text{ GPa}$$

$$E_{sh} = 207 \text{ GPa}$$

$$\left(\frac{\Delta L}{L}\right)_{sh} = -0.0174$$

$$\left(\frac{\Delta L}{L}\right)_{fil} = -0.0073$$

$$\sigma_{cu,y} = 21 \text{ MPa}$$

$$\sigma_{bz,y} = 119 \text{ MPa}$$

$$A_{cu} = 113.6 \text{ mm}^2$$

$$A_{bz} = 44.5 \text{ mm}^2$$

$$A_{fil} = 24.7 \text{ mm}^2$$

$$A_{sh} = 118.1 \text{ mm}^2$$

Values were obtained either directly or by extrapolation from Ref. 1 except for A_{sh} which was my own measurement of a sample at Airco/Westinghouse LCP conductor

References:

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3. P. A. Sanger, et al., IEEE Trans. Magn., MAG-17, 666 (1981).
4. M. M. Steeves, M. O. Hoenig, and C. J. Cyders, "Effects of Incoloy 903 and Tantalum on Critical Current in Nb_3Sn Cable-in-conduit conductors," in Advances in Cryogenic Engineering, A. F. Clark and R. P. Reed, eds., Plenum Press New York (1984).
5. M. O. Hoening, M. M. Steeves, and C. J. Cyders, "Nb_3Sn Internally Cooled Cabled Superconductor (ICCS) Technology I," presented at the 8th International Conference on Magnet Technology (MT8) - Grenoble, France, September 1983.
6. H. Shiraki, S. Murase, H. Oguma, T. Hamajima, N. Aoki and M. Ichihara "Strain effects of Forced Flow Nb_3Sn Conductor," Cryogenic Engineering (Japanese), 19, 225 (1984).
7. R. M. Scanlan, R. W. Hoard, D. N. Cornish, and J. P. Zbasnik, "Mechanical Properties of High-Current Multifilamentary Nb_3Sn Conductors," presented at the International Cryogenic Materials Conference, May 28-29, 1980, Upton, New York.

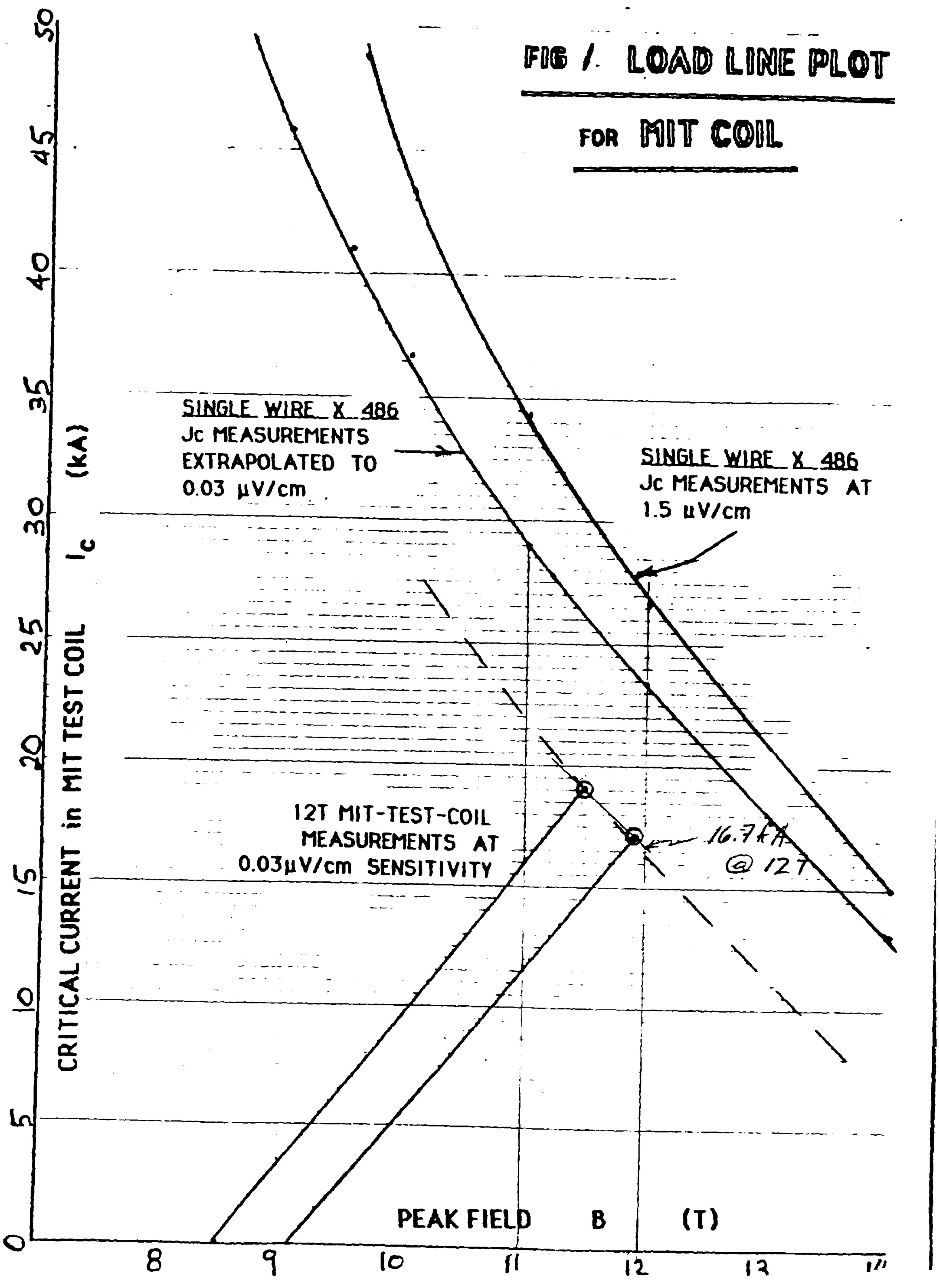
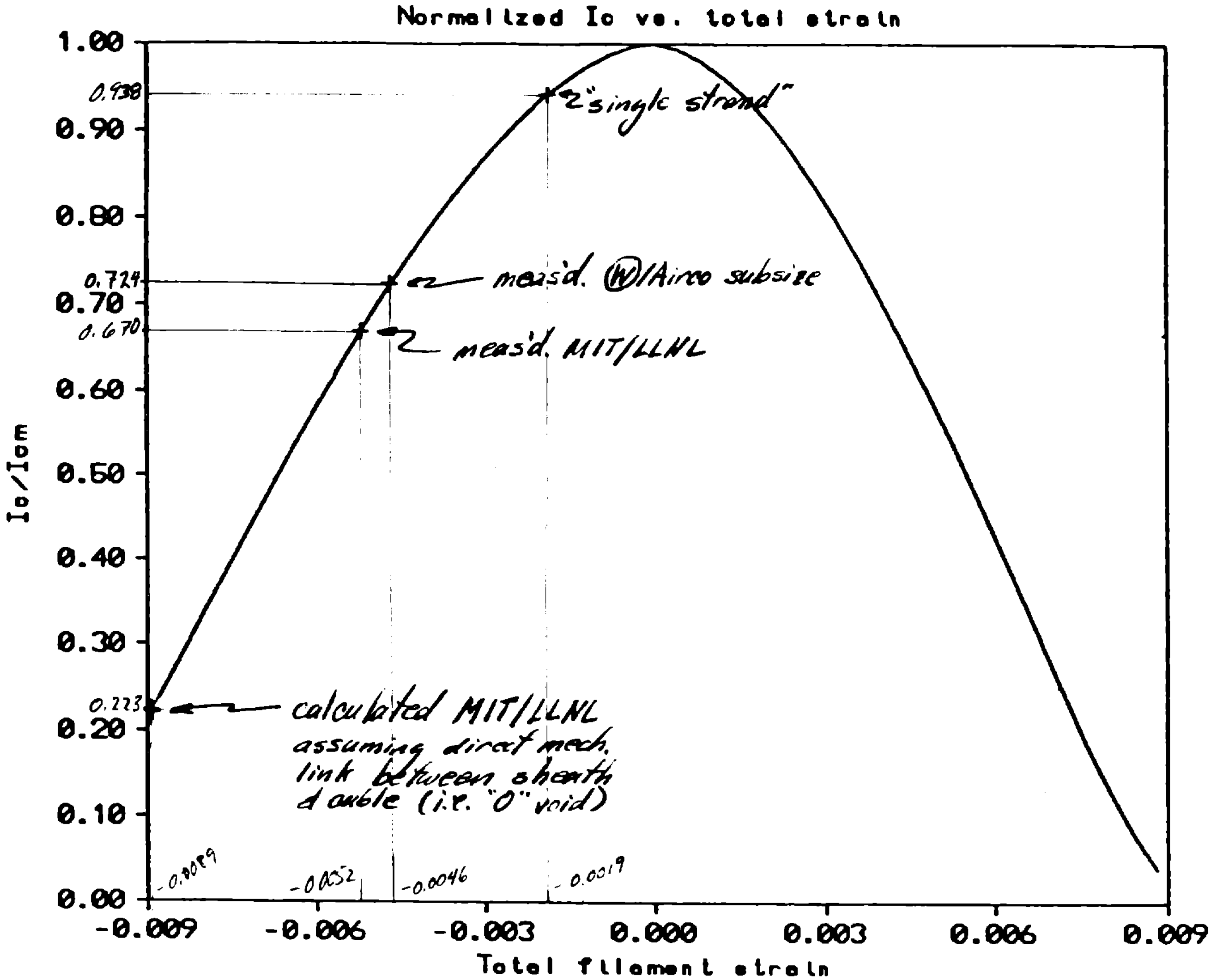


FIG 1. LOAD LINE PLOT
FOR MIT COIL
SINGLE WIRE X 486
Jc MEASUREMENTS
EXTRAPOLATED TO
0.03 µV/cm
SINGLE WIRE X 486
Jc MEASUREMENTS AT
1.5 µV/cm
12T MIT-TEST-COIL
MEASUREMENTS AT
0.03µV/cm SENSITIVITY
16.7 kA
@ 12T
CRITICAL CURRENT in MIT TEST COIL I_c (kA)
PEAK FIELD B (T)
0
5
10
15
20
25
30
35
40
45
50
8
9
10
11
12
13
14



$B_{c20_{max}} = 25\ T$

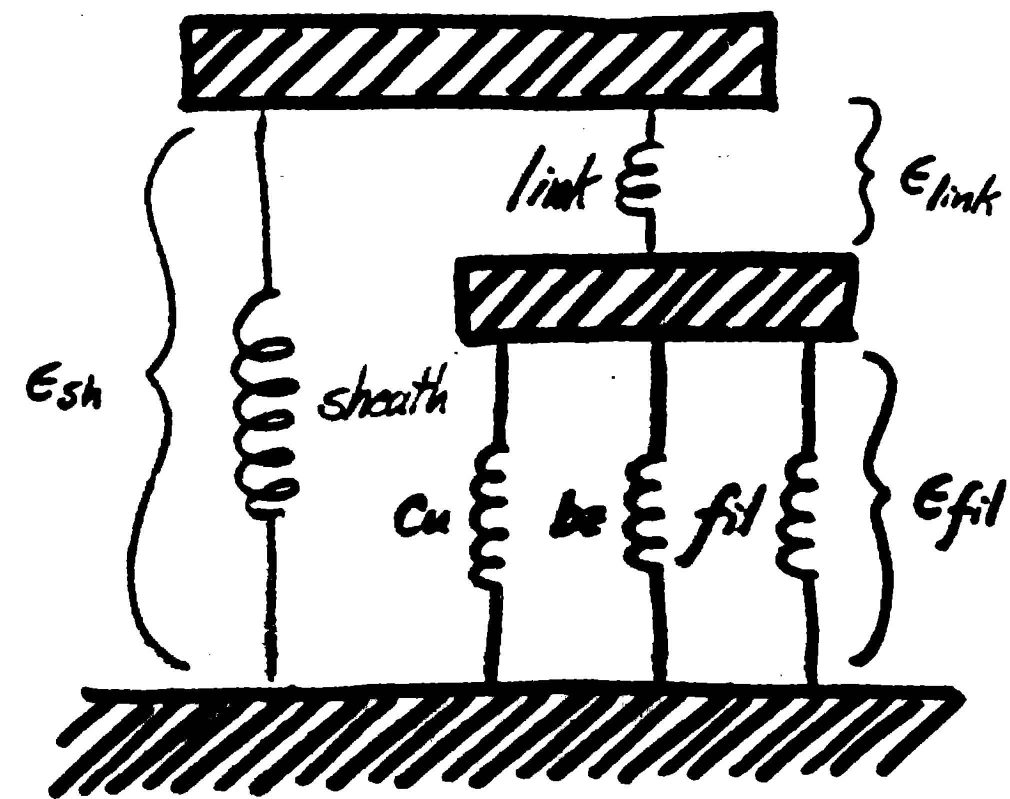
$T_{c0\ max} = 16\ K$

$B = 12\ T$

$T = 4.2\ K$

Fig. 2 Critical current strain dependence after Ekin using the above conductor parameters

Fig. 3. Model for cooldown strain



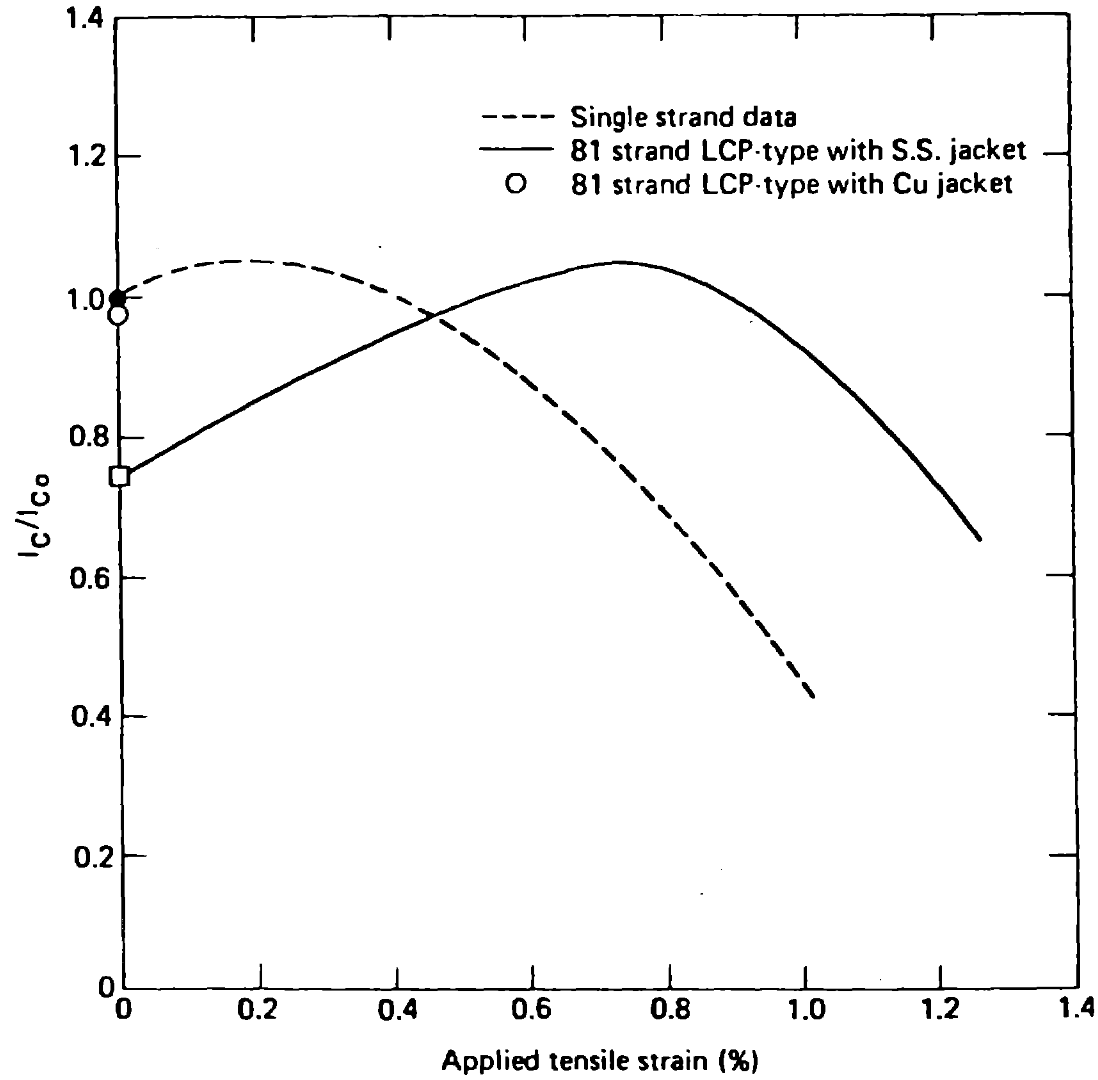


Fig. 4. The critical current (normalized to the value for zero applied strain on a single strand) is plotted as a function of applied tensile strain for a single strand and for 81-strand LCP-type conductors.